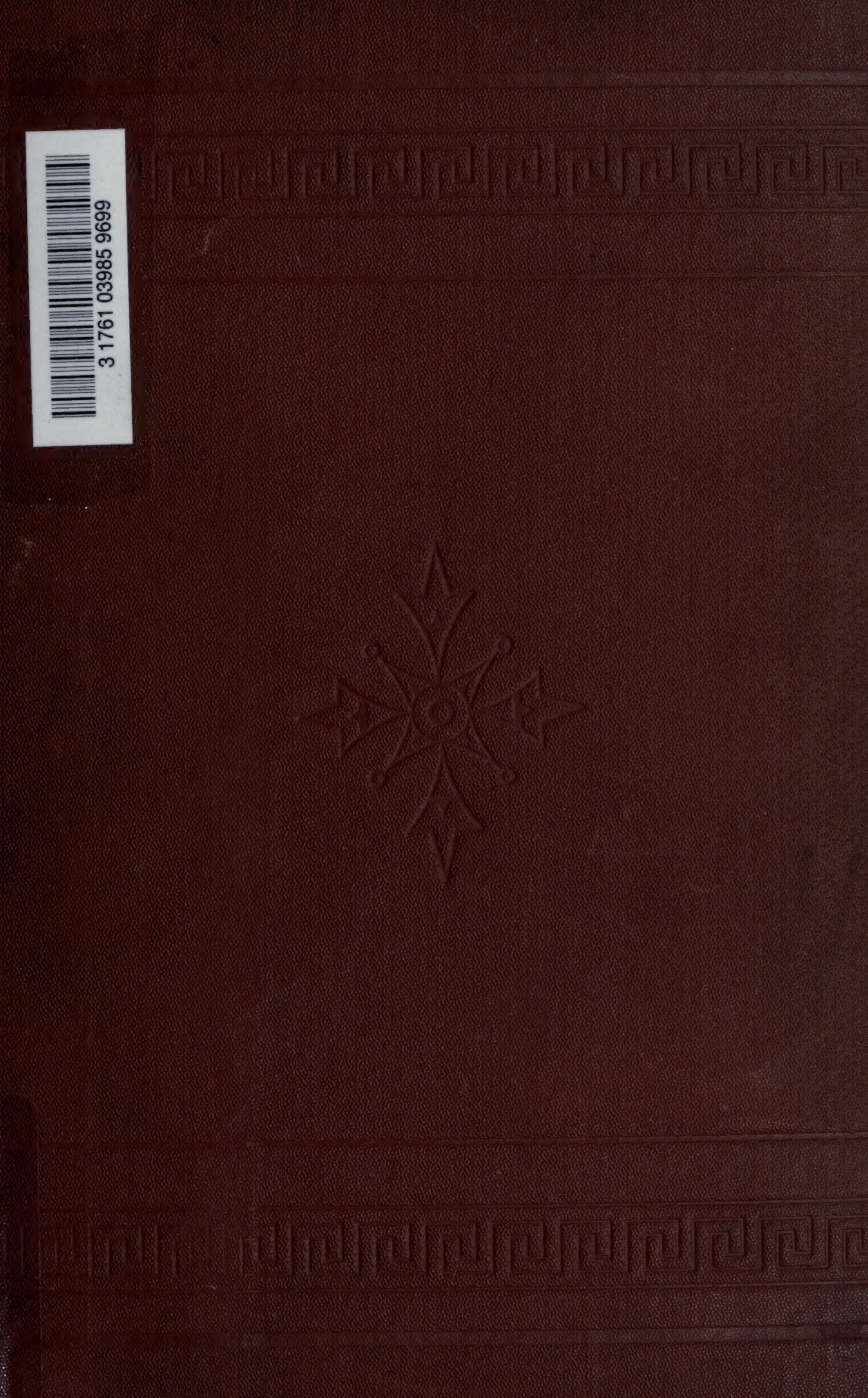


POWER DISTRIBUTION
FOR
ELECTRIC RAILROADS

BY

LOUIS BELL, PH.D.

THIRD EDITION. REVISED AND ENLARGED

NEW YORK:
STREET RAILWAY PUBLISHING COMPANY
120 LIBERTY STREET

BY THE
STREET RAILWAY PUBLISHING COMPANY,
NEW YORK.

PREFACE.

This little book is written in the hope that it may be of service to those whose daily work is concerned with the art of transportation, in which electrical traction is to-day so potent a factor. The part it may play to-morrow only the prophet can say.

The author has endeavored to set forth the general principles of the distribution of electrical energy to moving motors, to describe the methods which experience has shown to be desirable in such work, and to point out the ways in which these principles and methods can be co-ordinated in everyday practice. The art of correctly designing systems of distribution requires, more than anything else, skilled judgment and infinite *finesse*; it cannot be reduced to formulæ in which these terms do not enter as variables. The most that can be done is to sketch the lines of thought that, followed cautiously and shrewdly, lead to good results.

For the most part apparatus is too mutable to describe exhaustively, unless one is writing history. The reader will therefore find little of such detail, save in the frontier region which lies between established tramway practice and that greater field that stretches toward unknown bounds. Along that frontier experiment has blazed paths here and there, and we must note them carefully. We can see whither they lead, but dare not say how far.

The best advice that can be given to the engineer is to keep his eyes and ears open and never to let himself get caught out of sight of experimental facts.

PREFACE TO THE THIRD EDITION.

The past three years have been marked by nothing particularly startling in the way of innovations. Electric railways are more numerous and longer, and apparatus is on a bigger scale now than then, but the changes in methods have been few and trifling. The most notable line of growth has been in the increasing use of substations with rotary converters, sometimes with admirable results, sometimes with more energy than discretion. Storage battery auxiliaries have also been on the increase with varying economic effect. On the other hand, little progress has been made in heavy railway work, save in the multiplication of roads, and the problem of economical distribution for such work has not advanced toward solution. The substation idea has not yet been advanced beyond the crude conception of substituting motor for engine in an auxiliary station without improvement in the feeding system of the motors. This volume deals with principles and methods, and consequently, while it is pleasing to note that the motor has practically driven the locomotive off elevated roads, that third rail surface traction for heavy service is on the increase, and that long distance surburban roads have developed with splendid rapidity, one must regretfully admit that the examples of each given in the first edition are, save in unimportant details, as typical of current practice in 1900 as they were in 1896. Improvements are, however, already overdue, for we are still a long way from the final development of electric traction.

CONTENTS.

CHAPTER I.

FUNDAMENTAL PRINCIPLES.

Classes of distribution—Fundamental formulæ of distribution—Plate I, showing size of conductors for various losses—Losses with distributed and moving loads—Simple and branched lines—Irregular distribution of loads—Center of gravity of load—Location of centers of distribution—Networks and their computation—Variations of load, their nature and magnitude. 1–27

CHAPTER II.

THE RETURN CIRCUIT.

Nature of the return circuit—Conductivity of rails—Systems of bonding—Arrangement of bonds—Resistance of bonds and bond contacts—Earth resistance—Leakage of current from the rails to earth and other conductors—Electrolysis, its distribution and amount—Remedies—Supplementary wires—Continuous track—Welded and cast joints—The double trolley—Energy lost by bad bonding—Net resistance of bonded track—Track constants—Formula for complete circuit. 28–59

CHAPTER III.

DIRECT FEEDING SYSTEMS.

Systems of arranging feeders—Maximum and average drop—Load factor of the station—Wandering load—Computation of a feeder system—Extent of lines—Average load on lines—Center of distribution—Maximum loads—Trolley wire and track return—General feeding system—Reinforcement at special points—Plate II, chart for feeder computation—Cost of wasted energy 60–87

CHAPTER IV.

SPECIAL METHODS OF DISTRIBUTION.

CHAPTER V.

SUBSTATIONS.

CHAPTER VI.

TRANSMISSION OF POWER FOR SUBSTATIONS.

CHAPTER VII.

ALTERNATING MOTORS FOR RAILWAY WORK.

CHAPTER VIII.

INTERURBAN AND CROSS COUNTRY WORK.

CHAPTER IX.

FAST AND HEAVY RAILWAY SERVICE.

CHAPTER I.

FUNDAMENTAL PRINCIPLES.

The distribution of electrical energy for use in propelling railway cars is, by nature, a special problem. It deals with magnitudes and distances greater than are usual in other branches of electrical engineering, and, in addition, with the difficulties of a load that constantly shifts in amount and position. Consequently, the design of a distributing system is of singular difficulty.

In computing the area of conductors, one ordinarily assumes the load to be the only independent variable, but in this case the distance of transmission must be so considered, and both quantities are of the most erratic character.

The general equations can therefore only be solved within limits, except in special cases, and even then only by very judicious assumptions. It is therefore worth while to investigate these limits, their extent and the causes which impose them.

The conducting system of an electric railway, large or small, consists of three somewhat distinct parts—the working conductor, the return circuit and the feeders. By the first is meant that part of the total circuit from which the moving contact, carried by the car, immediately derives its current. Physically it is a wire or bar, uninsulated as respects the moving contact, and supported in any position—overhead, on the ground or under the ground—that circumstances may require.

The return circuit is, in a large proportion of cases, that which receives current from the wheels of the car, and is composed, partly or wholly, of the rails. In certain cases, conduit roads, double trolley roads and telpher systems, the working and return conductors are alike and of equal resistance. They may therefore be treated alike as parts of the working circuit. The ordinary return circuit calls for special investigation, because it is a heterogeneous conductor, unequal in resistance to the working conductor, and involving unusual complications.

The feeding system in railway work serves the double purpose of reinforcing the conductivity of the working conductor and equalizing the voltage at various parts of the system. It therefore must be deferred as a practical matter until the working system, which it supplements, has been considered.

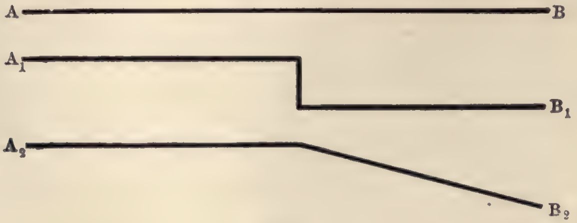


FIG. I.

Three classes of working systems are common, making the classification according to the nature of the distribution.

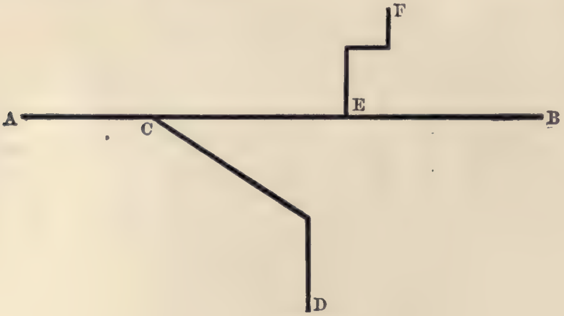


FIG. 2.

The first class is illustrated by the linear system, shown in Fig. 1. Ideally it is a straight line, A B, near some point at which the power station is generally situated. It may be modified by bends or curves, as in A_1B_1 and

A_2B_2, but whether it be a small tramway line along a single street, or a long interurban road, it retains as its main characteristic a single working line, not generally re-curved on itself, and subject throughout its length to fairly uniform conditions of traffic.

The second class is illustrated by the branched type, represented in Fig. 2. As shown, it consists of a main line, A B, into which run two branches, C D and E F. The branched distribution is the one most commonly met with in electric street railways of moderate size, and may assume an infinite variety of forms. It is the legitimate result of growth from the linear type, and, through all its modifications, is noteworthy in consisting of several lines which are neither interlinked, although often overlapping, nor subject to the same traffic conditions. Its conducting system is therefore essentially complex.

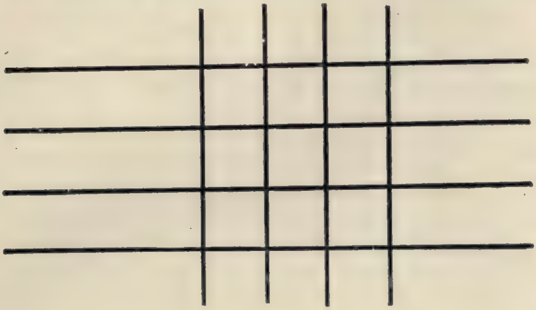


FIG. 3.

Finally, we have the meshed system, Fig. 3. Ideally, it is, as shown, a simple network composed of parallel lines crossing each other at right angles and at nearly equal intervals, and under fairly uniform conditions. Practically, the various lines composing the network cross at all sorts of angles and intervals, and are subject to all sorts of conditions of traffic. All networks however have this property, that they are composed of interconnected lines, so that the conducting system of any line can reinforce, and can be reinforced by, other systems. Fig. 4 shows that portion of the Boston network which lies within a mile radius from the Post Office as a center. It conveys an idea, better than any words, of the sort of network that occurs in practice. It differs totally from the networks usually met with in electric lighting, in that it is without any pretense of symmetry, either in configuration or load.

In all large installations one is likely to find all three types of distribution, usually a network in the center, and branched and linear distribution in the outlying districts. In laying out the system as a whole, each type must conform, as far as practicable, to its own conditions of economy, while the general feeding system must consider them all.

FIG. 4.

The starting point in any discussion of a conducting system for any purpose is Ohm's law in its simplest form

$$C=\frac{E}{R}.$$

In problems of distribution such as we are considering, the term involving R is usually the quantity sought, since the current and loss of potential are generally known or assumed. It is therefore desirable to transform this simple equation into some form which allows the ready substitution of the known quantities to determine the unknown. The resistance of any conductor may be written $R=K\frac{L}{A}$, in which A is the cross section, L the length and K a constant depending on the material considered and the units in which L and A are measured. If L is in feet and A in square inches the constant is obviously different from what it would be if L were taken in miles. The constant is, in practice, so taken that R will be in ohms when

L and A are in convenient units. In English-speaking countries it is usual to take L in feet and A in circular mils, *i.e.*, circles $\frac{1}{1000}$ of an inch in diameter. The constant connecting L in feet and A in circular mils with the resistance in ohms, for copper wire of ordinary quality at ordinary temperatures, is 11. This is approximately the resistance in ohms of a commercial copper wire one foot long and $\frac{1}{1000}$ of an inch in diameter. The exact figure is a trifle less, but the ordinary contingencies of temperature, joints, etc., make it desirable to take 11.

Substituting now this value of R in Ohm's law it becomes, reckoning the area in circular mils,

$$C = \frac{E}{11 \frac{L}{c.m.}} \text{ or, transposing,}$$

$$(1) \quad c.m. = \frac{11\ C\ L}{E}.$$

This is the fundamental equation of electrical distribution. It is like the original form of Ohm's law, strictly a linear equation, so that all the quantities are connected by simple proportions. Doubling E, for example, halves *c.m.*, while doubling L doubles *c.m.* A convenient transposed form is

$$(2) \quad C = \frac{c.m.\ E}{11\ L}$$

which determines the current which a particular line will carry without exceeding a given loss, and another,

$$(3) \quad E = \frac{11\ C\ L}{c.m.}$$

is convenient in figuring the actual fall of voltage. Throughout these equations E represents the fall in volts through the conductor under consideration, and L is always the total length of the wire, *i.e.*, double the length of the circuit, assuming a uniform return wire. For grounded circuits the equations give correct results for so much of the circuit as is exclusively copper—the grounded portion involves a different constant and must be taken up as a separate problem.

It is often convenient to have some simple expression connecting the area of a wire with its weight, so that the latter may be readily taken into account. By a fortunate chance, a copper wire, 1000 *c. m.* in section weighs almost exactly three pounds per 1000 ft. So if, in equation (1), we multiply the constant by three, and reckon L in thousands of feet, we obtain directly the weight of conductor per 1000 ft. Putting L_m for the length, to distinguish it from the former L reckoned in feet, we have

$$(4)\ W_m = \frac{33\,C\,L_m}{E}.$$

Thus, if we wish to transmit 100 amperes through 7000 ft. of conductor at a loss of 50 volts, the conductor must weigh $\frac{3300 \times 7}{50} = 462$ lbs. per 1,000 ft. The total weight of conductor is evidently $W_m\,L_m$, and since a simple way of getting the total weight, without reference to wire tables, is often desirable, we may re-write (4), as follows:

$$(5)\ W = \frac{33\,C\,L^2{}_m}{E}$$

which gives the total weight directly. These weight formulæ are very easy to remember and apply, and are accurate to about one per cent.

The diagrams of Plate I. put equations (1), (3), (4) in graphic form for ready reference. Four different values of E are assumed, and the unit of power is taken as 100 amperes. The chart is therefore independent of the initial pressure, and serves for transmission at any ordinary voltage. Distances on the horizontal axis represent length of circuit, *i. e.*, half the total length of conductor. To find area or weight per 1000 ft. of conductor required for a certain distance, take an ordinate at the required point on the distance scale and follow it up until it intersects the oblique line representing the assumed loss of voltage. The area of the necessary wire can then be read off on the left hand scale, and the weight per 1000 ft. on the right. The corresponding sizes of the B. & S. gauge wires are annexed to the former scale. In a similar

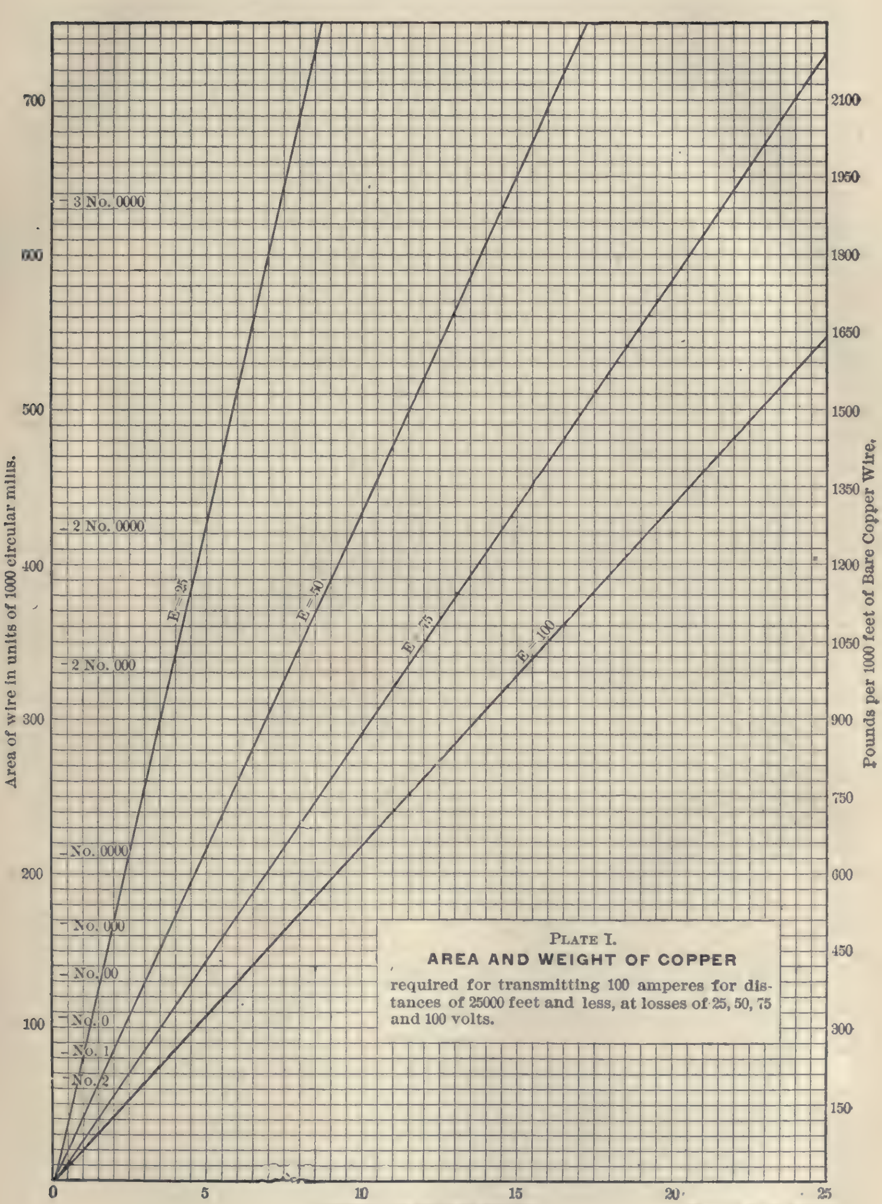


PLATE I.

AREA AND WEIGHT OF COPPER

required for transmitting 100 amperes for distances of 25000 feet and less, at losses of 25, 50, 75 and 100 volts.

Street Railway Journal

way the distance for which a given wire will carry 100 amperes at a given loss can be found, while the loss for a given wire and distance can be rapidly approximated by estimating the position of the intersection of the area and the distance co-ordinates with reference to the oblique lines. By noting that the area of conductor varies inversely with E, one can extend the working range of the chart. Halving the area shown for $E = 75$ gives, for instance, the area for $E = 150$, and so on.

Taking up now the case of linear distribution, it has already been shown that the fall in voltage in any conductor is directly proportional to the load and the resistance. If, now, a uniform line, A B, Fig. 5, be loaded at B, the voltage evidently decreases uniformly throughout its length. To make the example more concrete, the length A B is taken as 20,000 ft., and the voltage kept constant at A, *e. g.*, 500. Now, if the drop at B under the given load be 100 volts, a straight line drawn from C to D shows the state of the voltage at every point of the line. An ordinate erected at any point of A B and extended to C D shows the voltage of the line at the point selected, and that part of the extended ordinate cut off between C D and C F shows the loss in volts. If the load be transferred from B to some intermediate point of the line, an ordinate there erected will show the drop and the residual voltage at the new point. C E similarly shows the conditions for a terminal drop of 200 volts.

The average drop is evidently half the maximum in each case, since the minimum drop is 0, and the voltage varies uniformly.

Now suppose one has to deal with a load moving uniformly back and forth along A B. If the maximum drop be 100 volts, the voltage evidently moves uniformly along C D, and the average voltage is 450, since half the time the voltage is above this, and the other half an exactly equal amount below.

This case corresponds to a line traversed on a uniform schedule by a single car. Such however is not the usual condition of things. The normal condition of an electric road of any kind is a plurality of cars. This means that current is taken from the working conductor at a certain limited number of points. In general, these points represent approximately equal loads and, so long as the time table is maintained, are approximately equidistant. In Fig. 6, the uniform straight conductor, A B, is loaded, not, as in Fig. 5, at one point, but at ten equidistant points, the loads being assumed equal, as they would be quite nearly if each load were a car on a level track.

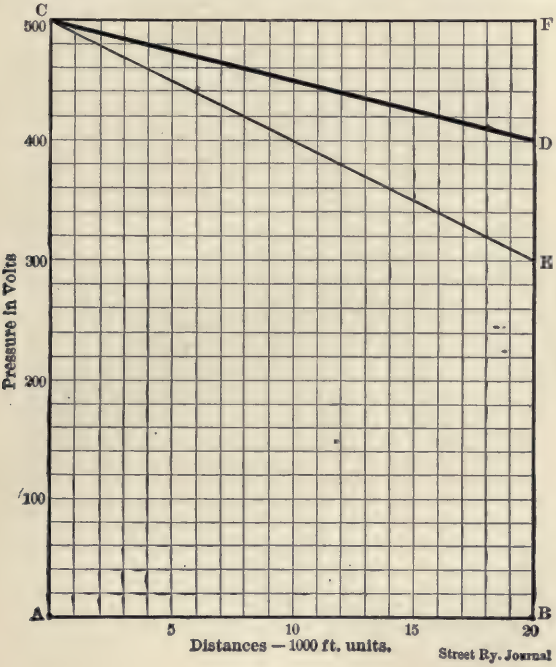


FIG. 5.

Here the conditions of fall in voltage are radically different from the conditions of Fig. 5. At the power station, A, the full current for the entire load is supposed to be delivered at a uniform pressure of 500 volts. Assume the total current to be 200 amperes, and the resistance of each of the uniform sections to be 0.05 ohm. The first section carries the whole 200 amperes, and the drop C R is 10 volts. The second section carries but 180 amperes, and the loss is 9 volts, and so on, until the tenth section carries 20 amperes, and the loss has diminished to 1 volt.

Mapping these successive falls of potential on Fig. 6, the curved line, C D, is formed, showing the consecutive values of the potential on A B. C E, a prolongation of the drop in the first section, shows the result of concentrating the whole load at B.

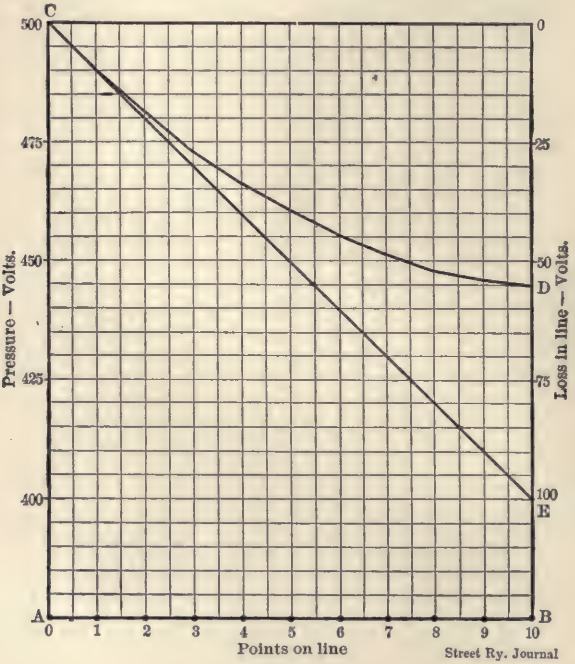


FIG. 6.

In such a uniformly loaded line the drop is found as follows: If C is the total current and there are n sections in the line, then $\frac{C}{n}$ is the current taken off for each section, and $\frac{C}{n} r$ is the drop due to that current, where r is the resistance of each section. The drop in the first section from A is $10 \frac{C}{n} r$, in the second section $9 \frac{C}{n} r$ and so on; *i. e.*, for the whole n sections the total drop must be

$$(6)\ E = \frac{C}{n} r (1 + 2 + 3 \ldots n)$$

But the sum of this series of integers is well known, being $\frac{n(n+1)}{2}$. Hence, substituting and reducing, we have

$$(7)\ E = \frac{C r}{2} (n + 1).$$

This gives the total drop produced by n uniform loads uniformly spaced and aggregating C amperes.

It is generally convenient to have working formulæ give the cross section of conductor directly, since that is most frequently the quantity to be determined. Equation (3) can readily be transformed for this purpose as follows:

$$(8)\ R = \frac{11\,L}{c.m.}.$$

But since the R here concerned is the total resistance, and not the resistance per section r, as in (7), we may write,

$$r = \frac{11\,L}{(c.m.)n}.$$

Then substituting this value of r in (7) and reducing, we have

$$(9)\ c.m. = \frac{11\,C L}{2\,E} \left(\frac{n+1}{n}\right)$$

This equation gives the area of conductor required for C amperes supplying a line of known length equally loaded at n points at any required terminal drop.

For a large number of sections $\left(\frac{n+1}{n}\right)$ approaches unity, so that, for a given current in amperes and a given terminal drop, the copper necessary for a uniformly distributed load is one-half that required for the same load concentrated at the end of the line. As the number of sections increases, too, the likelihood of obtaining a disarrangement of load sufficient to disturb the terminal voltage much, decreases. The effect of a uniform motion of all the loads on the terminal voltage is small. So long as the schedule is uniform and is adhered to, the worst that can happen is a transformation of the system into half the original number of sections. Suppose in Fig. 6 all the load points of odd numbers to be moving to the right and all those of even number to the left, at uniform speed. Then after each point had moved half a section, there would be five sections each loaded with a pair of coincident loads. Applying (7) to the data of Fig. 6, $E = 60$, assuming the sections uniform. As, however, the first section would be but three-fourths the length of the others, the real loss would be 55 as before. Another equal movement and the ten sections appear in their original relation. Another and we have the five sections, but with an initial section one-fourth the length of the others and total loss of 45 volts. Next would come a ten-section arrangement, but with the first load at A, and $E = 45$, and so on. The upshot is that while the terminal voltage oscillates through a range equal to the drop in the first section, the final effect on the average drop of uniformly moving the loads is the same as loading each section at the middle point or increasing n indefinitely. Hence, in a line with uniformly spaced and uniformly moving loads, we may assume

$\left(\frac{n+1}{n}\right) = 1$ in (9) and write

$$(10)\ c.\,m. = \frac{11\,C\,L}{2\,E}$$

or, transposing,

$$c.\,m. = \frac{L}{2} \cdot \frac{11\,C}{E}.$$

That is, the area of the line can be calculated for average terminal drop just as if the load were concentrated at its middle point. Hence, for all practical purposes, by making this assumption, equations (1), (4), (5) can be used in calculating the line.

To keep the voltage approximately uniform over a linear system of distribution is comparatively easy. In the most favorable case, a number of uniform loads moving uniformly, the drop is half that met with in the most unfavorable distortion of the load, *i. e.*, bunching at the end of the line. This latter condition brings the worst possible load upon the station, barring short circuits. Although long stretches of uniform conductor often occur in railway practice it is usual to reinforce the working conductor by feeders variously arranged, as will be shown later. Such feeders were very necessary in the early days when trolley wire as small as No. 4 was used, but now, when No. 00 is very commonly employed, elaborate feeding systems are less necessary for linear working. The most important linear distributions are likely to come in long interurban roads, which often demand special methods of feeding. Whatever these may be, the uniform working conductor is of sufficient importance in every system to warrant this discussion of its general properties.

FIG. 7.

As a corollary to this general investigation, it is evident that in dealing with any linear system such as A B, Fig. 6, the best point for the power station is at the middle point of the line, since under the conditions of uniform load supposed, this point would give the smallest average drop. Since L in such case is one-half of its value when the whole line is fed from A, the total copper by equation (5) is reduced to one-fourth the amount for the same loss.

Considering now the branched type of distribution, shown in Fig. 2, it is best to take it up in the simplest available form. This, Fig. 7, shows a main line, A B D, with a branch, B C, which is straightened and made parallel to the main in order to more clearly show their relations. Unless the branch is of such magnitude and position as to require special feeders, it is supplied with current from the main linear system. In a few cases the service on a branch is from B to C and back. More generally it is from C to A and back, a part of the cars being devoted to a through branch route. On the section A B, the load is the sum of those due to each line of cars. Beyond B there are two independent linear systems.

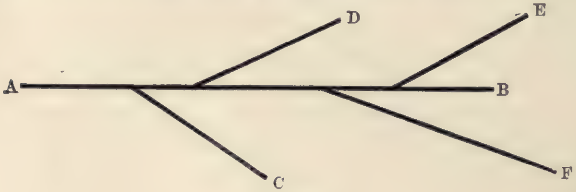


FIG. 8.

If there are m cars on the route A D, and n cars on the route A C, then the load on A B, due to both lines, will be

$$m\frac{\overline{AB}}{AD}+n\frac{\overline{AB}}{AC}$$

and the loads on B C and B D respectively will be

$$n\frac{\overline{BC}}{AC} \text{ and } m\frac{\overline{BD}}{AD}.$$

Consequently, if the section A B is computed for this load according to (10) we shall get the proper conductor for the assumed loss E. The lines B C and B D can then be computed for losses E_1 and E_2. The values of E, E_1, E_2 are usually taken with the condition imposed that $E+E_1$, $E+E_2$ shall be less than a certain specified maximum. A more general method is that of Fig. 8. Here there is a line, A B, with branches running to C, D, E, F. The loads are l, m, n, o, p, amperes respectively. A B, A C, A D, A E, A F, are now considered as separate, each subject to its own conditions. Taking now a drop for each line, according to the dictates of economy or convenience, and figuring the conductors from (10) with the respective currents, an area is found for the conductor belonging to each line. Then the cross section of copper required from A to the first branch is $[c\,m]_1 + [c\,m]_m + \ldots$. That from the first to the second branch is $[c\,m]_m + [c\,m]_n + \ldots$ and so on. In practice the conductors would be installed of the nearest convenient size, neglecting small variations of E from the calculated amount at the termini of the various lines.

The same procedure applies to all sorts of independent lines radiating and fed from a common center, whether or not these lines have any sections in common.

We have thus far assumed all lines to be uniformly loaded all along their lengths. It often happens however that for some cause a line is loaded unequally. In the long run, grades partially compensate themselves, since as many cars run down by gravity as go up by the expenditure of extra power, so that their effect shows more in the variations of power required than in the total amount. Not infrequently, however, from the effect of grades, curves or local cars in an extended system, there is a regular demand for extra power at some point of the line. This is shown in Fig. 9. Here the line, A B, is divided into ten sections, each equally loaded, except that at 8 the load is three times the normal. Now it has just been shown that a uniformly distributed load is the same in effect as if it were concentrated at the middle point of the loaded line; that is, the electrical loads, like mechanical ones, act as if concentrated at their center of

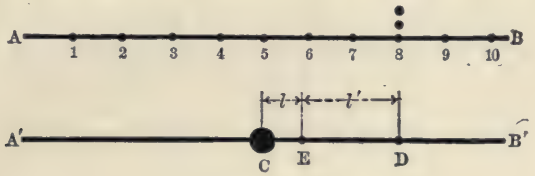


FIG. 9.

gravity. Hence we may represent the above case by A′ B′, Fig. 9. If c be the normal load of each section, then a load of $10\,c$ will be concentrated at C while a load of $2\,c$ is at D. Hence, following out the principle of center of gravity, the system requires for a fixed value of terminal drop the same extra area of copper as if the whole load, $12\,c$, were concentrated at E, a point chosen so that $2\,cl' = 10\,cl$. The same result is reached in many cases more simply by figuring the normal uniform load as if concentrated at C, and then treating the load $2\,c$ at D as if it were on a separate line, as in computing branches. This is the best procedure when grades and other extra loads are superimposed on normal and regular traffic.

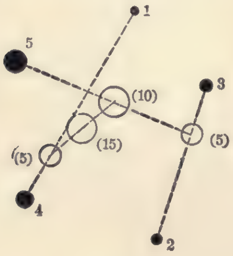


FIG. 10.

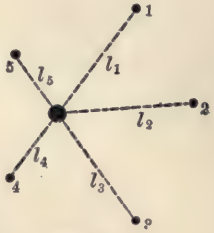


FIG. 11.

But the principle of center of gravity has another and a broader application.

In any case of scattered load the center of gravity of the system is the proper point from which to distribute the power, at least in so far as this point gives the minimum weight of copper for a given loss. For instance, in the line of Fig. 9, E is the point from which the power should be supplied, whether direct from a generator or from a feeder, if A′ B′ is but a single part of a large system. The center of gravity of two points on a line is found by the ordinary balancing principle, as in Fig. 9. The center of gravity of any number of points in a plane is found by an extension of exactly the same method, as shown in Fig. 10. Let there be, for example, five load points in value respectively 1, 2, 3, 4, 5; required the center of gravity of the system.

Take any two points, as 2 and 3, and find their mutual center of gravity, just as in Fig. 9. This will be located at a point at which the whole value, 5, of the 2-3 system may be assumed to be concentrated. Now find the center of gravity of this point and 5; this will be at a point at which the weight will be 10. Then taking 1 and 4, the resultant weight will be 5. Finally, balance these resultants and the center of gravity of the entire system is found at 15. The order in which the combinations are made is of no consequence, since a given system can have but one center of gravity. Now, suppose the points 1, 2, 3, 4, 5, are supplied from a common source O, Fig. 11, through lines l_1, l_2, l_3, l_4, l_5. Referring to equation (5) the total weight of copper in any line, as l_1, may be written $W = K c l^2$, where K depends on the uniform drop assumed. For any number of load points thus connected to a center O $\Sigma W = K \Sigma c l^2$. But this is directly proportional to the moment of inertia, $\Sigma m l^2$, of the loads considered as weights, about O as an axis. Now the moment of inertia of any body about any axis is composed of the sum of two terms, viz., first, the moment of inertia of the parts of the body around its center of inertia and, second, the moment of inertia of the whole mass concentrated at its center of inertia, about the axis chosen. Therefore, the minimum moment of inertia for a given set of loads is obtained when the axis coincides with the center of inertia, thereby causing the second term to disappear. Hence the total weight of copper required for supplying, at a given loss, any system of loads is a minimum when the system is fed from its center of gravity. And the penalty for disregarding this law is severe, as will presently be shown.

For example, take the case of a circular area with an electric system made up of equally and uniformly loaded lines radiating from a power station at the center. It has already been shown that the cross section of copper needed for a uniformly loaded line is the same as if the load were concentrated at the center. The weight is proportional to the cross section multiplied by the length. In the circular distribution of Fig. 12, therefore, the area of the conductors is proportional to $\frac{1}{2}r$, the radius of the circle, while their lengths equal r. Hence, the weight of copper for such a distribution is directly proportional to the product of these factors and equals $\frac{1}{2}\,\mathrm{K}\,r^2$.

If, now, the system is fed from another point than O the center, such as A, the weight of copper will be proportional to the new moment of inertia, and, since this is made up of the sum of the terms mentioned, the copper will be doubled when $d^2 = \frac{1}{2}r^2$, i. e. when $d = \frac{r}{\sqrt{2}}$. It will be multipled by 3 when $d^2 = r^2$ and so on, rapidly increasing. The following table gives the relative weights of copper corresponding to a few values of W.

$$\mathrm{W} = 1,\ d = 0$$
$$\text{“} = 2,\ \frac{r}{\sqrt{2}}$$
$$\text{“} = 3,\ r\sqrt{\tfrac{3}{2}}$$
$$\text{“} = 4,\ r\sqrt{2}$$
$$\text{“} = 5,\ r\sqrt{\tfrac{5}{2}}$$
$$\text{“} = n,\ r\sqrt{\tfrac{n}{2}}$$

In any sort of distribution the mechanical analogue furnishes a solution of the copper problem in the ways just indicated.

It at once appears from these considerations that the cost of copper runs up with disastrous rapidity if the center of distribution is distant from the center of load. From the data given one can figure out readily the extra investment in real estate that it will pay to make in order to put the station near the center of load.

The facts set forth are a powerful argument for the economy of an alternating current distribution with high tension feeders, if such a system can be rendered available for ordinary railway work. The main objection to locating a center of supply at or near the center of gravity of the load is the cost of site. For a regularly constituted generating station this cost is often prohibitive, so that it is far cheaper to endure the great increase of copper necessary for feeding from a distance. If the central plant be reduced to a substation for supplying an alternating current to the working conductors, the space taken up is so trivial that its cost is almost nominal. The reducing transformers for a capacity of 1000 k. w., together with switchboard and all necessary station apparatus can easily be accommodated in a room ten feet square, if compactness is necessary. Nor is there any need of extreme care in the matter of foundations, since there is no moving machinery, save motors for ventilation, in such a substation.

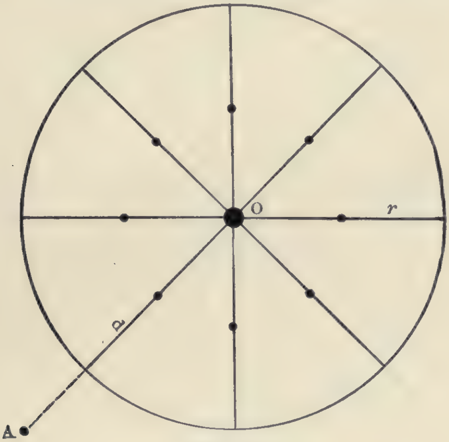


FIG. 12.

Even if the day of alternating motors for railway service be delayed far longer than now seems probable, there are not a few cases in which substations with motor-generators are preferable in point of economy to an immense investment in feeders. At present prices of apparatus such a condition will be met far oftener than would at first glance seem probable. In large cities, where there is a strong and growing tendency to force all feed wires underground, the cost of installing and keeping up conduits adds very materially to the disadvantage of elaborate feeding systems from a distant point.

Another class of cases in which special attention to the location of power station is needed may be found in the interurban and cross country roads now becoming common.

Generally the distribution is linear or branched, rather than a network. We should not, however, assume that the power station should lie at the middle, end or any other point on the line of the road. It very often happens that the center of gravity of the load, which is the most economical point for distribution, as we have just seen, is not on the line at all. For example, take the line shown in Fig. 13. It consists of three sections connecting, we may suppose, four towns, A, B, C, D. The configuration of the system is here determined by the topography of the region, the amount of business at each point, and similar considerations familiar in the art of railway location. We may suppose the load of each section concentrated at its middle point as before, forming the load points, *a*, *b*, *c*. Suppose the loads to be as follows: $a = 15$, $b = 10$, $c = 5$. These loads may be taken in any convenient units provided the same units are used throughout.

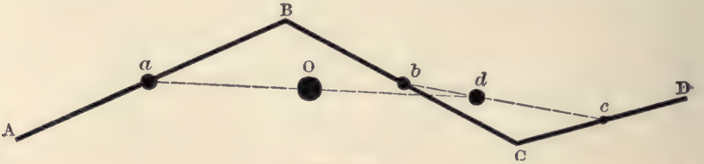


FIG. 13.

Now, proceeding as before, draw *b c* and locate the center of gravity of the loads, *b* and *c*. This proves to be *d*, where the concentrated load is 15. Then drawing *a d*, the center of gravity of the system is found to be at O, quite off the line of the road, although not inconveniently distant from B. In other instances the center of gravity might very readily be as far from any of the towns, A, B, C, D, as each is from its neighbor. This example, however, shows a common characteristic of long lines.

The network type of distribution found in railway practice is quite different in character and needs from a lighting network. It is, save in a few instances, such as Fig. 4 (see page 4), much less complex and is always much more irregular in load. In a well ordered central station for electric lighting, every street in the business district has its main, and the load, while far from regular, does not exhibit the extreme variations found in electric railway work.

The general solution of even a simple network, to find the current (and thence the drop) in each line due to one or more known load points, involves a most forbidding amount of tedious computation. But for the purpose in hand exact solutions are not needed so much as easy approximations.

Consider, for example, the simple network of conductors shown in Fig. 14. A is here the source of supply, either the station or the end of a feeder. The load is distributed along the lines, A D, A E, D E, D F, E F, D C, F B and C B. Such a circuit may be said to consist of three meshes, and it contains eight currents which we may call i_1, i_2 etc. In lighting practice it is necessary, knowing the load to be supplied by each line, to figure the conductors so as to maintain uniform voltage throughout the network. This involves algebraic processes too complex for convenient use; in fact the complete solution is a very pretty problem in determinants, which those interested may find elucidated in Maxwell's "Treatise on Electricity and Magnetism," and somewhat simplified in a paper by Herzog and Stark, published in 1890. For railway work the conditions are, fortunately, simpler. We know, or can assume with sufficient accuracy, the normal distributed load on each of the lines. But we are absolved from any necessity for keeping closely uniform voltage throughout the system, since, even were it a matter of more importance than it ever is, it could only be accomplished by using an enormous excess of copper, for a large part of the load is liable at any time to be concentrated on almost any part of the network.

Two conditions must at all events be fulfilled. First, each one of the lines, A D, A E, etc., must be able to carry its own proper load without exceeding a standard drop; and, second, the sum of the distributed loads must be carried at certain points, which can be approximately prejudged, without exceeding a certain maximum drop.

It must be noted that the conducting system of a railway differs from that of a lighting plant in having a much greater proportion of feeders to mains. In fact the working conductor of a railway is generally of quite limited carrying capacity. Practically, in laying out a network like that of Fig. 14, one has to cut loose from lighting precedents and deal with a special problem.

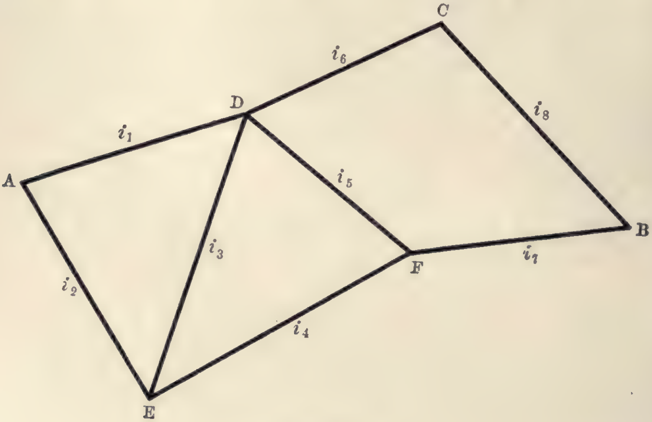


FIG. 14.

Following the first of the conditions just named, a convenient first step is to compute the conductors as isolated lines, on the assumption that i_1, i_2, i_3, etc., are the currents due to the normal load on each line. This furnishes the skeleton, as it were, of the conducting system. This work can often be simplified by bearing in mind the main lines of traffic and treating as one their component conductors. For instance, in Fig. 14, if A be the station it may be convenient to take A D C B as a single conductor carrying a load $i_1+i_6+i_8$, and A E F B as another loaded with $i_2+i_4+i_7$. D E and D F may then be taken separately.

Now, this skeleton must be padded with reference to the second condition mentioned. Suppose that traffic is liable to be congested at or near B. This point is fed by the two main lines in multiple. If the drop chosen for these in making the skeleton would mean a drop at B sufficient to seriously impēde traffic, enough copper must be added to relieve this condition. Just where this addition should be made requires the exercise of considerable discretion. If F is a point where congestion is also to be feared the line, A D F, should be strengthened, being the nearest route. If C be threatened, A D C should be reinforced. In either case the addition should be sufficient to put B out of danger. In any case i_3 and i_5 should be considered with reference to the lines, A D and A E, and the drops in D E and D F so taken as to keep them at good working pressure in spite of any excessive demands near the terminus of the system. In other words, for railway work it is nearly always possible to split up a network into a combination of linear systems and branches, since the loads are, or may be, so uncertain that fine discrimination in minor lines is out of the question.

A good development of this splitting principle may be found in Fig. 15, which is a network of three meshes composed of two parallel lines, A and B, cross tied by the lines, C D, E F, G H, I J. Let A be a feeder and B the trolley wire and we have the well known "ladder" system of feeding in. As, in practice, C D, E F, etc., are very short compared with C E, E G, etc., the system may be regarded as composed of A and B in parallel, the only qualification being due consideration of the possible drop in B between a load point and the two nearest feeding points. But we may suppose A and B to run in adjacent streets and the former to be connected to another trolley wire on its own street, then a track to run along G H, and so on until the full network is developed. At each stage of complication the system may be considered as composed of one or more mains with branches, without sensible error, the inaccuracy of the assumption being negligible compared with the uncertainty produced by the irregular load.

The variations of load in an electric railway system are so prodigious as to render the most careful calculations only roughly approximate. They are, in general, of three kinds. First, the momentary variations due to accidental changes of load incident to the nature of the service. Second, periodic general variation of the aggregate load caused by the varying conditions of service throughout the day. Third, shifting of the load to various points of the system, concurrent with the daily variations in total load, but bearing to them no simple relation.

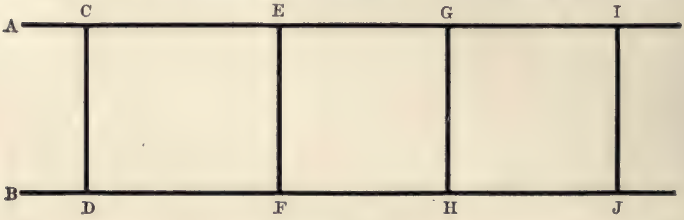


FIG. 15.

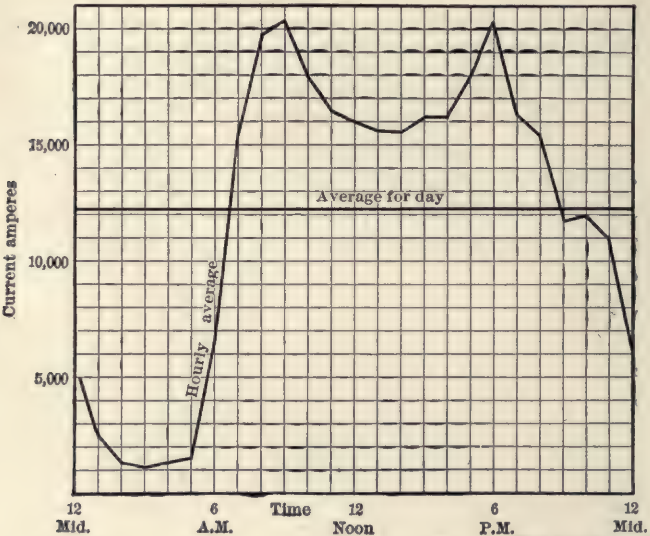
The momentary variations are constantly occurring from minute to minute, almost from second to second. They are most considerable in street railway systems operating but few cars, and their amplitude may then be equal even to the maximum total load, and occur in a fraction of a minute. Such a condition may easily exist in a plant operating eight or ten cars. As the number of cars increases, the chance of so great variations diminishes, although somewhat slowly. In very large systems, the extreme amplitude of these oscillations of load may be reduced to twenty or twenty-five per cent. of the total load, but they can never disappear entirely. Their effect on the design of the conducting system is but small, for the voltage does not have to be kept closely uniform, and the conductors will be laid out for the average load based on the average consumption of energy per car. With a normal drop so computed and with care taken to allow a reasonable margin for maximum loads, these variations of the first class need not constitute a serious embarrassment.

The diurnal changes of load based on average readings in which the minor oscillations are suppressed, are great in amount and of much interest. They are due to the habits and occupations of the community served, and often exhibit very curious peculiarities. Further, they are almost as strongly marked in very large systems as in quite small ones and serve to determine the relation of average to maximum load, which in turn determines the allowance which must be made for drop at extreme loads. Even under very favorable circumstances the difference between average and maximum load is great. This is very forcibly shown in Fig. 16, which gives the load line on one of the largest electric railway systems for a December day, just before the holidays.

The minimum load is quite uniform from 2 A. M. until 5 A. M. and is only about six per cent of the maximum. At about 5 A. M. the load comes on quite suddenly and continues to rise until about 9 A. M., when it begins to fall, and keeps diminishing until about 2 P. M. Then it rises, slowly at first and then more rapidly until it reaches a second maximum, about equal to the first, at 6 P. M. Then it falls somewhat irregularly until only the night cars are left.

The average load for the twenty-four hours is about six-tenths of that at the two maxima. This difference is what must be kept in mind in providing a due factor of safety in the conductors. The load line is not, of course, invariable, being subject both to accidental and yearly variations, but, in spite of these, it preserves its characteristics and the value of its "load factor" with remarkable uniformity. In small systems there are practically no night cars, the service being generally about eighteen hours. Were such the case in Fig. 16, the "load factor" would be materially improved, rising in fact to about three-fourths on this supposition. But in small plants the day mimimum is relatively smaller than in Fig. 16, so that the load factor is worse. Indeed it only too frequently falls to one-quarter or one-third in roads operating five to ten cars. Any value of load factor over one-half may be considered good in any but the largest plants.

In long roads operating a few large cars or trains at high speed, the load is subject to smaller casual variations, but the load factor is apt to be low by reason of the great change made by the stopping or starting of a single load unit. The load during the period of acceleration is likely to be about double the running load even with carefully handled motors, and as this period is often several minutes, there is an excellent chance for the superposition of several such loads.



Street Railway Journal

FIG. 16.

More serious than any others are the variations in the location of load, since these may cause a heavy call for power at some distant part of the system. Such shifting of the load occurs in nearly all cases of linear distribution, and has already been noted, but it also occurs on all sorts of systems, and is the more serious as it is less to be regularly expected. A single blockade may fill a limited district with stalled cars, and when at last it is broken the call for power is of a most abnormal kind. It does not appear strongly marked on the load line, but shows in the shifting of load from one feeder to another. On systems of moderate size this shifting of load may be very serious. For example, through the baseball season many roads will find nearly their full output demanded at the ball park once or twice a week. The next maximum output may be at the other end of the system, to accommodate some special celebration. Even in a large network, at certain hours, during, and just before, maximum load, the bulk of the load will be within a small district, and within the same district only when the same causes produce the shifting.

This wandering of the main load over the system is one of the most exasperating factors in the design of the conductors. It may easily amount to the concentration of a quarter or third of the total load at some quite unexpected point. It can be dealt with only by a minute study of the local conditions, which generally will furnish some clue to the probable magnitude and position of such wandering loads. Whatever may be the general conditions of drop, the conductors must be so distributed as to prevent the system breaking down when loaded in some abnormal manner at some unusual point. No theory can take account of such occurrences; their ill effects can be obviated only by good judgment, which is of more value than many theories.

CHAPTER II.

THE RETURN CIRCUIT.

The outgoing circuit of an electric railway has just been discussed in its more general relations. Before investigating the proportioning of the working conductors it is necessary to look into the return circuit. Up to this point it has been assumed that this is similar to the outgoing system as it is in the case of motor systems in general.

In nearly all electric railway practice it has been the custom to employ the rails and earth as the return circuit, since the former are good conductors and necessarily in contact with the car wheels, and the latter is as necessarily in contact with the rails.

In some cases two running contacts are employed as in the double trolley system, conduit roads, some recent elevated roads, and the like, but in most instances the total circuit of any railroad consists of the outgoing system of copper conductors and a return circuit consisting of the rails and their environment.

Now the conductivity of an iron or steel rail is computed with tolerable ease, but the rest of this heterogeneous system is most uncertain. It consists, near the surface, of bond copper, tarnished surfaces, iron rust, rock, dirt, dirty water, mud, wet wood and promiscuous filth, and deeper down of all sorts of earthy material, and in cities various sorts of pipes for gas, water, etc.

In the early days of electric railroading the resistance of this strange assortment was assumed to be zero on the theory that the earth was the conductor concerned and was practically of infinite cross section. This was shockingly far from the truth and although data are rather scarce, we may properly take up the return circuit piecemeal and see what the actual state of things may be.

First as to the rails. Mild rail steel is a very fair conductor. Weight for weight it is, comparing the commercial metals, just about one-seventh as good a conductor as copper. Now a copper wire weighing one pound per yard has an area of about 110,000 c. m.; hence an iron bar weighing one pound per yard is equivalent to about 16,000 c. m. of copper, very nearly equal to No. 8 B & S gauge. This enables us at once to get the equivalent conductivity of any rail *neglecting the joints.*

The resistance of a copper wire of 16,000 c. m. is roughly six-tenths of an ohm per thousand feet. Hence the resistance of any single rail in ohms is, per thousand feet

$R = \frac{.6}{W}$ where W is the weight per yard.

Or since two rails form the track $R = \frac{.3}{W}$

That is, if the rail used weighs sixty pounds per yard the track resistance is approximately $\frac{1}{200}$ ohm per thousand feet. For convenience the relation between weight of rail and equivalent copper is plotted in Fig. 17. The maximum figure is for mild rail steel. Of late there has been a tendency to use a harder steel rather high in manganese. This lowers the conductivity by no small amount, sometimes to one-tenth that of copper, for which the minimum in Fig. 17 is arranged. In close figuring the conductivity should be measured, and specified in ordering rails.

These relations enable one to figure the drop in the track, *neglecting joints,* by the formulæ already given. For this purpose the distance in the formula should be, of course, the actual length of track, not the double length as when a return circuit of copper is figured. Thus one would separate the outgoing and return circuits and compute the drop in them separately. For simplicity it is however desirable to make allowance if possible for the return circuit, incorporating it in the constant of the original formula so as to make but a single calculation.

The figures just given emphasize with tremendous force the need of thorough bonding of the track in order to take advantage of its immense conductivity. In the early electric railways this was terribly neglected, the bond wires sometimes being as small as No. 6 and even of galvanized iron. Bonding is of very various character. Its most rudimentary form is shown in Fig. 18. In this case the bonds merely united the ends of adjacent rails, each line of rails being bonded separately. The improvement of Fig. 19 is quite obvious, for in Fig. 18 a single break compelled one rail to carry the return load. The cross bonding of Fig. 19 adds somewhat to the weight of copper required, but ties the rails together so that no single break can be serious and nothing save a break from both rails on the same side of the same joint can really interrupt the circuit. A very large amount of track has been so bonded, although at present the usual construction is shown in Fig.

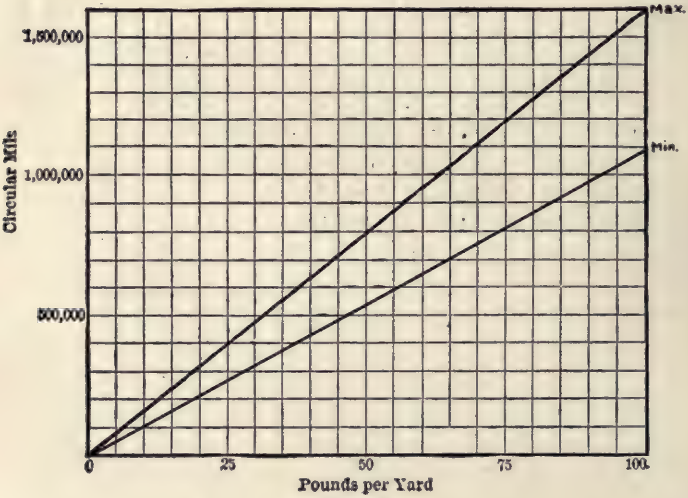


FIG. 17.

20. The supplementary wire effectively prevents "dead rails." In modern practice the bond wires are often as heavy as No. oooo, and are generally tinned to prevent corrosion. All joints in the wire are soldered and the rail contacts made as perfect as possible. It is perfectly clear that the supplementary wire is of little value as a conductor compared with the rails, but it is of service in mitigating the effects of bad joints. In a few cases this supplementary wire is reinforced by a heavy copper conductor laid alongside the track and connected at intervals to the supplementary wire as shown in Fig. 21. If the joints made by the bonds and rail are very bad this extra copper may be of service, but good joints render it quite unnecessary. The value of the rails as conductors is so great that every effort should be made to utilize them to the fullest possible extent.

FIG. 18.

FIG. 19.

FIG. 20.

FIG. 21.

The seriousness of the joint question may be seen by a moment's reflection upon the data already given. There are about thirty-three joints per thousand feet of rail. This means sixty-six contacts per thousand feet between rail and bond, in addition to the resistance of the bond wire itself. Now, the resistance of a sixty pound rail per thousand feet is, as we have seen, only $\frac{1}{100}$ ohm, in decimals 0.01. If there should be even one-ten-thousandth of an ohm resistance in each joint between bond and rail, the total resistance would rise to 0.016 ohm per thousand feet. Add to this, the actual resistance of, say, sixty feet of bonding wire No. 0, and the total foots up to 0.022 ohm, more than doubling the original resistance. If the joints were here and there quite imperfect, as generally happens, the rail resistance might easily be increased far more.

One would be thought lacking in common sense who needlessly doubled the resistance of an overhead circuit, but in the rail circuit far more atrocious blunders are only too common. A few years ago it was frequent enough to find bond wire simply driven through a hole in the web of the rail and headed on the outside. Fortunately, the need of care here is now better realized and in the last few years the name of the rail bond is legion. Most of the contacts are modified rivets, not infrequently supplied with some sort of wedging device to ensure a tight contact. They are, most of them, good enough if properly applied, but a careless workman can easily destroy the usefulness of even the best bonds. The bond contact proper is often quite distinct from the bond wire and is generally given a greater cross section than the latter, to ensure an ample contact with the rail. Figs. 22 to 25, inclusive, show some of the best current forms of bonds. Fig. 25, the "plastic" bond, is composed of a layer of a species of amalgam retained by an outer wall of cork and squeezed into intimate contact with rail and channel plate. It gives a singularly low resistance contact.

As to the real resistance of a bonding contact, experiments, as might be expected, vary enormously. The resistance of the bonding wire is, of course, determinate, but that of the contact is most irregular, varying with every kind and size of bond and with the thoroughness with which the mechanical work is done. No part of electric railway construction deserves more careful attention. Cull-

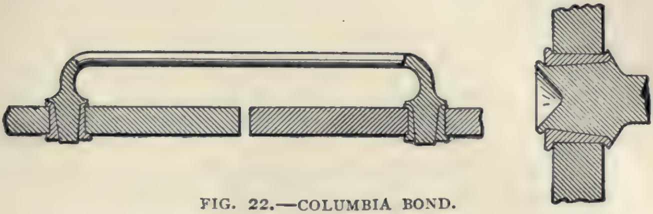


FIG. 22.—COLUMBIA BOND.


FIG. 23.—CROWN STRANDED BOND.

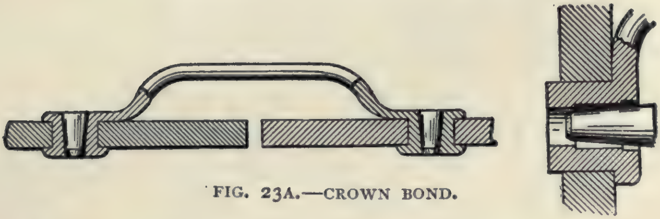


FIG. 23A.—CROWN BOND.


FIG. 24.—BROWN PLASTIC BOND.

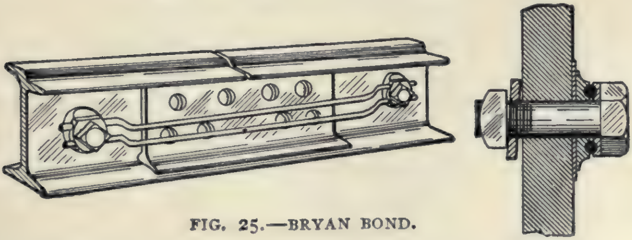


FIG. 25.—BRYAN BOND.

ing the values of bond resistances from experiments on the bonds shown we get the following table:

BOND RESISTANCES.

Fig. 22 = 0.000131 ohm.
“ 23 = 0.0001.
“ 23A = 0.000247
“ 24 = 0.00006
“ 25 = 0.000175

These resistances are for the complete bonds newly set.

As nearly as may be judged, the resistance of a single contact, carefully made, can be counted on to be considerably less than .001 ohm. With bond plugs of large surface well set, it would seem safe to count upon a resistance not exceeding .0002 ohm. per contact.

The bonding wires should be as short as can be conveniently handled. The advantage of lessened length appears strongly in the results from Fig. 23. Such bonds under the fish plates are more dificult to apply than bonds around the fish plates, but are of low resistance and well protected. As to size, there is little reason for using anything smaller than No. 000 or No. 0000. With about a foot of No. 0000 at each joint, and thorough contacts carefully made, the resistance of bonds ought to be about as follows per thousand feet.

66 bond contacts = .0132
33 ft. 0000 wire = .00165

Total 0.0148 ohm.

This is about one and a half times the resistance of a thousand feet of sixty pound rail and corresponds well with actual tests of well bonded track. It is quite near the truth to assume that under average circumstances of good construction the bond wire and contact resistance may aggregate about twice the resistance of the rails themselves.

As regards the earth there is great misconception both as to its conducting power and the part it takes in modifying the rail and bond resistance which we have just been considering. Outside of the metals there are no substances that have even fair conducting properties. That is, all other so-called conductors are very bad compared even with a relatively poor conductor like iron. For example, carbon in the form of graphite or gas coke, is usually considered a very fair conductor, yet it has several hundred times the resistance of iron, while nitric acid and dilute sulphuric acid, the best conductors among electrolytes, have many thousand times the resistance of iron. The acid last mentioned has a specific resistance of about 0.4 ohm for a cubic centimeter, while the resistance of a cubic centimeter of iron is only 0.00001 ohm. Water, even when dirty as it is found in the streets, would show a specific resistance of 1000 ohms or more. Earth, rock and other miscellaneous components of the ground are even worse, so that it is at once fairly evident that it would take an enormous conducting mass even of water to approximate the conductivity of a line of rails.

Even in theory the mass of earth really available for conducting purposes is somewhat limited, for if a current be passed between two earth plates, the current density decreases very rapidly as the lines of flow depart from the direct path between the plates. It has long ago been shown, too, that when such a current is established between, let us say, a pair of metallic balls sunk in the earth, the resistance of the circuit does not vary much with the distance apart of the terminals, but depends greatly on the surface of the ground connections. Numerous experiments, too, have shown that the earth is so heterogeneous, so broken up into strata of varying conductivity, that the current flow takes place mainly along special lines, the general mass taking very little part in the action. If, for example, a ledge of rock is in the line between earth plates, save for possible crevices filled with water, it is practically a non-conductor.

At various times and places the value of a true earth return for railway and similar work has been thoroughly tried and has generally been found to be practically *nil.* In two cases the ground plates were sunk in considerable rivers which formed return circuits for lines in each case about four miles in length. The ground plates themselves were of ample area, in one experiment several hundred square feet, and gave every opportunity for good contact with the water. The applied voltage in each set of experiments was 500 to 550. The resulting currents were insignificant and the resistance of the earth return proved in one case to be about 85 ohms, in the other but a few ohms less.

In another more recent experiment the terminal stations were about 3000 ft. apart. An attempt had been made to use an earth return for a motor circuit, with the usual result, and the failure led to investigation. The experiment was arranged as in Fig. 26. At A and B were carefully arranged ground plates in duplicate. One of each pair was sunk in a well, the other imbedded in a mass of iron filings in damp earth. At 1, 2, 3, 4, 5, stations 500 ft. apart, grounds were made by driving large iron bars deep into the earth. The voltages employed were various, from 60 to 150 volts direct current, and alternating current from a small induction coil. The results were nearly coincident in all the sets of experiments and showed the following curious state of affairs:

Stations.	Res. ohms.	
A . . B	92.4	Ground plates alone.
A . . B	121.0	Well plates alone.
A . . B	66.8	Both well and ground plates.
A . . 1	201.6	
A . . 2	374.0	
A . . 3	92.	
A . . 4	506.3	
A . . 5	180.0	

The resistance is evidently not a function of the distance nor of anything else that is at all obvious. The only feature that is what might be expected, is the tolerably regular effect of putting both sets of earth plates in parallel as exhibited in the first three lines of the table. The resistances at the intermediate stations show how hopeless it is to predicate anything of earth resistance except that it is too high to be of any practical use save for trivial currents such as are employed in telegraphy.

Imagine the stations A and B, Fig. 26, to be connected by a track consisting of a pair of sixty pound rails thoroughly connected and put in parallel with the circuit via the earth connections. At best this has a resistance of 66.8 ohms while that of the track should be at worst only a few tenths of an ohm. Following the ordinary law of derived circuits, it is clear that the current returning via the earth is only a minute fraction of one per cent of the whole. If the track could be continuously in good contact with the earth throughout its length somewhat more current might be coaxed into the earth return by taking advantage of all the fairly conducting streaks and strata. In rare instances the earth under the track has been found in such condition as to have a material amount of conductivity, enough to lessen the drop through the rails very perceptibly. Such cases, while well authenticated, are so uncommon as to be of small value save in showing the enormous irregularity of earth resistance, and the utter lack of any well defined laws governing it. And in practice, track is so laid that it is not in good electrical contact with the earth as a whole. Fig. 27 shows in section a type of track construction which has been very widely used. The rail is laid upon a longitudinal stringer timber to which it is spiked firmly. The stringer is secured to the cross ties by angle irons. The ties are well tamped with clean sharp gravel which is packed around them and the stringer, and forms a foundation for paving of block granite set closely in upon the rail. Here the material in contact with the rail and surrounding it for some space is very badly conducting except when the track is flooded.

FIG. 26.

Fig. 28 shows another track construction, which would appear to give even worse conduction between rail and earth than Fig. 27. The rails are here supported at each tie by cast iron chairs, without an intermediate stringer, and the ties are set in concrete, while rail and chair are surrounded by coarse gravel on which the paving is laid. In no modern track is the rail in contact with better conductors than hard wood, gravel or stone. Consequently there is very little tendency for current to be shunted from rails to earth, unless the former are very badly bonded, for the paths in derivation are bad and there is little difference of potential between any two points of the track to impel branch currents of any kind. Of course, if one attempts to use the two rails as outgoing and return leads, the condition is wholly changed, for the full difference of potential then exists between two neighboring rails and there must be a very large amount of leakage. In fact, if there is any considerable difference of potential between the rails or between them and any other conductor, there will be a perceptible flow of current, even through as bad a conductor as damp gravel, if the path be not too long.

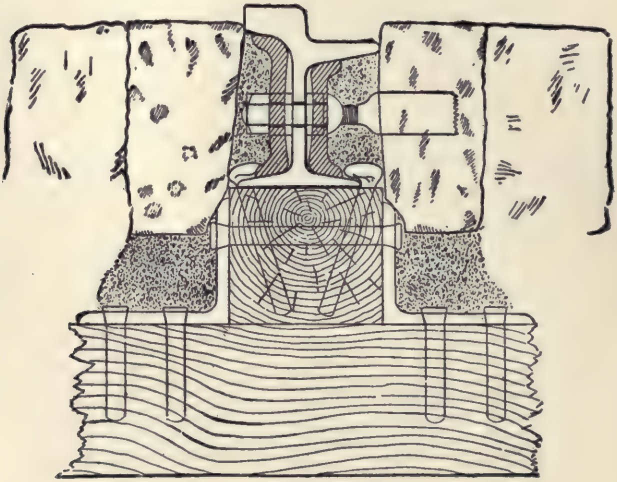


FIG. 27.

Thus it is that while ground plates along the track according to early usage are insignificant in modifying the conductivity of the return circuit, there may be, if the rails are poorly connected, very perceptible flux of current from the track to, for instance, a water main running parallel to it and but a few feet away. Fig. 29 shows this state of things. Let A B be the track and C D a water main half a dozen feet below the level of the track. The resistance between any particular points of A B and C D is at all times large, owing to the high specific resistance of the material between them, but the area between A B and C D in a long stretch of track is so great that if the fall in potential in A B is not very slight indeed, there will be a considerable flow of current into and along C D. To take a concrete example, let A B be twenty rods long, and suppose C D to be a foot in diameter and six feet distant from A B. The total area of material in direct circuit would probably be a strip 100 metres long and not less than a metre wide. Such a strip would contain a million square centimetres area and we then have to compute the resistance of a block of bad conductor a million square centimetres in section and perhaps averaging 200 cm. long. This we can regard as built up of a million strips, each one centimeter square and 200 cm. long, connected in parallel. The total resistance would then be the resistance of one such strip divided by 1,000,000. In fact the resistances of these elements would be very various and the currents would flow in all sorts of irregular lines, but we are deal-

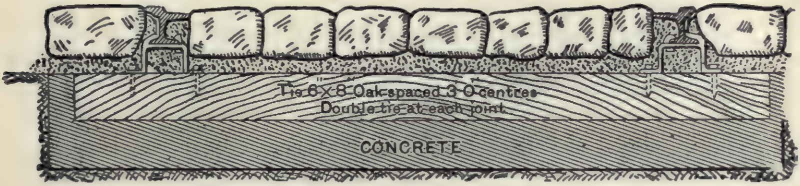


FIG. 28.

ing here only with the average result. Suppose the material has a specific resistance of a thousand ohms per cubic centimetre, then the resistance of one element would be 200,000 ohms, but the whole mass would have a resistance of only one-fifth of an ohm; hence if there should be between track and pipe an average difference of potential of ten volts, an amount sometimes exceeded in real cases, there would be within the distance considered a flow of fifty amperes between track and pipe.

As large pipes may weigh several hundred pounds per yard, it is clear that their conductivity cannot be neglected, although in most cases it has no noticeable effect on the resistance of the system. In any case, these extraneous metallic conductors cannot properly be counted as a part of the circuit, except under very unusual conditions, since flow of current to them is highly objectionable, as will presently be shown.

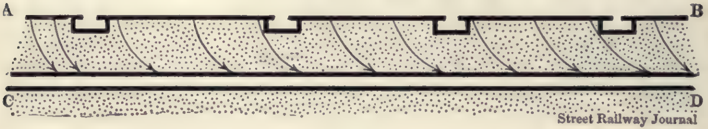


FIG. 29.

To sum up the matter of earth return, properly so called, the earth, so far from being a body of high conductivity, useful for eking out the carrying power of the rail return, is, for most useful purposes, to be regarded almost as a non-conductor. Its specific resistance is so high and irregular that it is of no value as part of the return circuit, while its conducting power in great areas comes into play only in an unpleasant and troublesome way. The conduction which occurs is very irregularly distributed and varies greatly from time to time. For all long lines of railroad and for many small street railway systems, the earth may be left entirely out of account, and in large street railway systems it is generally a source of anxiety. In the early days of electric railroading quite the opposite view was often held and roads were constructed accordingly. In reality the bonding was then so generally inefficient, that probably even the earth may have improved the general conductivity. Experience has shown that the view here presented is generally the correct one, and the realization of it has done much to improve general practice. Possibly interference with telephone circuits did much to prolong faith in the earth as a conductor, but the telephone deals with millionths of amperes, which are quite insufficient for operating street cars.

Recurring to Fig. 29, and granting the conditions to be such that a current flows from track to pipe at some point in the system, that current must leave the pipe and either pass back to a part of the track having a lower potential or to some other conductor by which it may work its way back towards the station.

Now wherever an electric current leaves a metallic conductor for one which owes its conductivity, as does the earth, to the presence of liquid, the surface of the former is corroded—gnawed away by the chemical action set up by the current. Hence the pipe under consideration would soon show a surface pitted with rust, and eventually the corrosion would extend through to the inner surface of the pipe and start a leak. Similarly the rails are corroded from the exit of the current, but the result is not of much consequence.

This matter of electrolytic corrosion of water pipes, gas pipes and other buried conductors is serious in very many electric railway systems, so serious that it is worth detailed study as one of the gravest factors bearing on the design of the return circuit. One would naturally suppose that the actual amount of damage done by the comparatively small currents distributed over a large space, would be rather slight. So it would be if it were intermittent, but when the electrolytic process goes steadily on week after week and month after month, the aggregate result is somewhat formidable. One ampere flowing steadily from an iron surface will eat away very nearly twenty pounds of metal per year. So, in the case of conduction to a pipe just investigated, the resulting corrosion would amount to *half a ton per year*. This destruction would be done in the surfaces of exit from the pipe and if the conditions were such as to limit these surfaces to a comparatively small area the local damage would be very serious.

Electrolytic corrosion of underground conductors by stray currents was first noticed in the case of lead covered telephone cables in Boston by I. H. Farnham, to whose researches much of our knowledge of the subject is due.

Lead is attacked at the rate of about seventy-five pounds per ampere per year, so that the result is extremely marked. Fig. 30 gives a diagrammatic view of the circuit through such a cable. Part of the current used on the railway circuit passes from the rails to the cable and thence along it to the neighborhood of the motors, where it passes back to the track and the moving cars. The mischief is done at this point and not while the current is flowing in the cable. The effect produced is a severe corrosion of the lead covering of the cable taking place irregularly upon the surface and forming pits, which may penetrate the sheath and destroy the insulation of the cable.

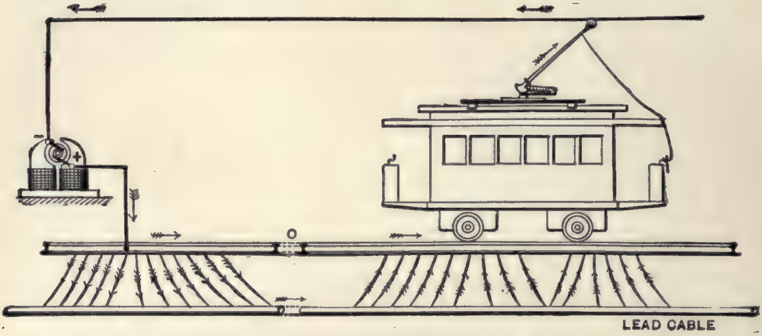


FIG. 30.

Investigation showed the state of things on the Boston system to be very interesting. At the time, the positive poles of the dynamos in the power station were connected with the rails so that the current passed into them and thence to the pipes and cables, emerging from them at various points in the system. The corrosion was thus widely distributed, but from local conditions of conductivity was most apparent in spots. Careful measurements of the potential between the track and the cables were made in a large number of places with the result shown in the map (Fig. 31). Near the power stations the flow was from track to cables, but over the main area of the city it was from cables to track, giving a large area in which corrosion might be expected. Differences of potential as high as five volts were observed, while experiments in other cities have shown as much as twenty-five volts. It is interesting to note that one of the first experiments tried to relieve this electrolytic action was to sink in the earth ground plates connected to the cables in the hope that the current flow would take place mainly through them. The potential differences even at points quite near these plates were practically unchanged, showing very plainly the intense badness of the earth as a conductor, which has already been pointed out.

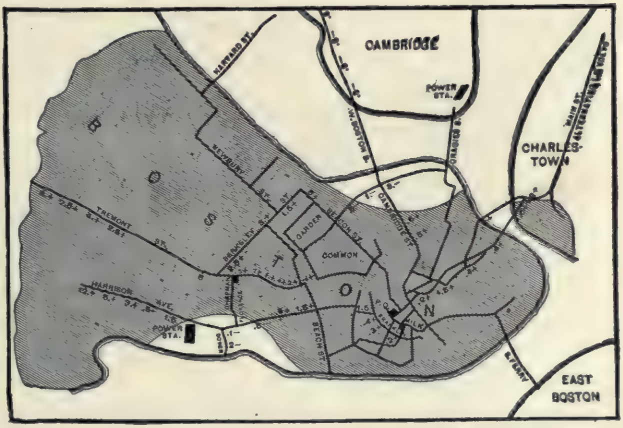


FIG 31.

The method of treatment which proved most effective in reducing the electrolytic effects, was first to locate the trouble as nearly as practicable in definite areas and then to check it in these areas. In the first place the dynamo connections were reversed so that the stray current would enter pipes and cables over the most of the system, but would leave them en route for the negative terminal of the dynamo only in the districts immediately surrounding the power houses. Thus it would be certain that the damage would be limited to known areas which could be attacked locally with success, instead of being scattered where the trouble would be hard to locate and harder to remedy. Even within these areas conduction and consequent electrolysis is likely to be very irregularly distributed, so that serious trouble may occur at one point when points near by are apparently unaffected.

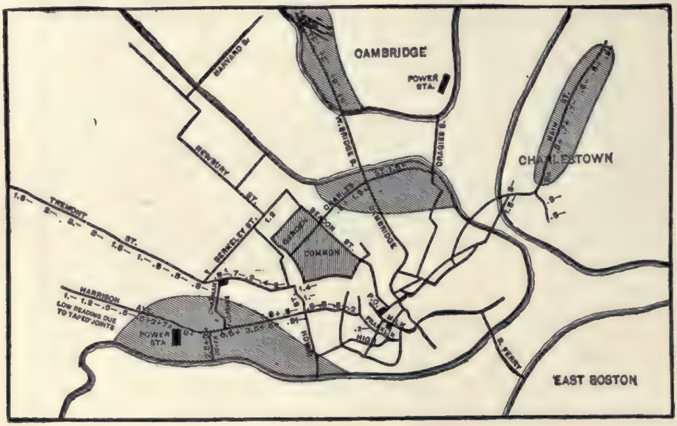


FIG. 32.

Fig. 32 shows the result of this change. The "danger areas" shown here as before by shading on the map, are comparatively small, although within them the differences of potential were quite as great as before. Now the problem was to lead the current back to the dynamo without compelling it to leave the cables, and corrode them at the points of exit. To this end, large copper conductors were extended through the danger area and thoroughly connected at intervals to the telephone cables. The result was excellent, since the stray currents, instead of passing from the cables through the earth to the track, took the easier path through the supplementary conductors.

A measurement of the current thus collected from the telephone cables into a main ground wire from the station showed over 500 amperes capable, if flowing continuously, of eating away 37,500 lbs. of lead per year. And as this current did not include that which found its way to water and gas pipes, the real amount of current which left the rails and wandered home through underground conductors was considerably larger than the figure mentioned, probably several times as great. The distribution of this current is so irregular from place to place, as indicated on the map, that it would be very hard indeed to estimate the total proportion it bears to the whole current on the system. So far as data are available however they indicate that we would not be wide of the truth in saying that ten to twenty per cent of the current on the system may follow other paths than that through the rails and bonds. Even more than this may appear in occasional instances. So while the earth helps the return circuit directly but little, buried conductors may help very materially, perhaps to their own serious detriment. It should be remembered that the electrolytic action is not necessarily proportional to the differences of potential such as are noted on the maps. The places most injured depend on local conductivity and some of the worst instances recorded have occurred where the measured potential difference was only one or two volts.

Figs. 33 and 34 give a graphic idea of the kind of damage that is done to pipes by electrolysis from stray currents. Fig. 33 shows the effect of corrosion on an iron gas pipe, and Fig. 34 that on a lead water pipe. Both are from photographs of the "horrible examples." As the action tends to become concentrated in spots, a pipe may be perforated in a rather short time. Iron water pipe has sometimes been riddled in five to eight months. That this is easily possible may be readily seen, for suppose that conditions are such as to get in a certain spot a flow of half an ampere in a space of one square foot. Suppose the pipe to be ⅝ in. thick, therefore weighing about twenty-five pounds per square foot of surface. If the electrolytic action were perfectly uniform the pipe would be reduced to an unsubstantial shell in a single year, and since the corrosion always shows irregular pits the pipe would almost infallibly be perforated in six months. Very curious differences exist between electrolytic actions in various situations, depending on the chemical conditions in the soil. Sometimes the action produces a thick dense coating of ordinary rust which almost suspends the electrolytic process, while elsewhere the products of decomposition are more soluble, and the work goes on until the iron is eaten away leaving a mere shell of the contained carbon and electrolytic debris generally.

FIG. 33,

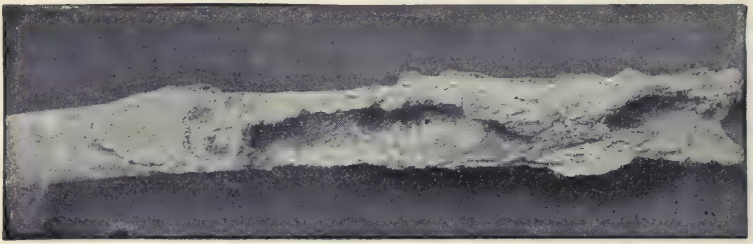


FIG. 34,

It is worth while to note that surface protection of pipes by painting with asphalt and the like has been shown by the Boston experience to be practically worthless, as the corrosion seems to work under the film, which can never be made really insulating to any useful extent.

In spite of the quite perceptible assistance that may be rendered by underground pipes to the general conductivity of the return system, every effort should be made to avoid it. For, even if the various lines of pipe are protected by the supplementary wire method described, there may be electrical differences at the joints of the pipes quite sufficient to cause local corrosion in serious amount. Joints in water pipe are better mechanically than electrically and the currents flowing through them may, as we have seen, be rather heavy. Take for example Fig. 35. Suppose that owing to oxidized and dirty surface of contact the joint A has a resistance of .005 ohm and that a current of one hundred amperes is flowing through it in the direction indicated by the arrow. The fall of potential through the joint would then be .5 volt, lines of current flow would be set up as shown by the dotted lines and a ring of corrosion B C would be set up on the positive side of the joint. Half a volt is quite enough to do the work, and though the action might be slow it would be sure. In point of fact the lead calked joints used in water pipe may readily show a resistance ten or twenty times that just assumed, sometimes even an ohm or more, a case still more serious.

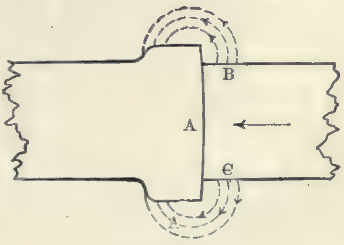


FIG. 35.

Therefore all conduction by pipes ought to be avoided as far as possible unless they are electrically continuous. Even if they are, protection by supplementary wires is somewhat risky since while it may relieve trouble in the conductors so connected it may enhance the danger to neighboring pipes not thus protected.

Joints between pipes of different materials are especially dangerous, for instance between cast iron and cement lined sheet iron. Under exceptionally unfavorable conditions joints have been eaten out in as short a time as six weeks.

Liberal use of supplementary wires has great use as an emergency measure, applied to systems already existing, but here, as generally, an ounce of prevention is worth a pound of cure. The proper return circuit of the railway should be made so good that the stray currents shall be quite negligible, and all methods of palliating their evil effects should be considered secondary in importance and to be shunned rather than courted. It must not be understood that these methods are condemned, for they may be of much use, but they should be employed only to deal with the residual currents after they have been reduced to the lowest practicable terms by means of improving the track circuit.

The main point of such improvement lies in the connections between rail and rail. If the resistance of the bonds and their contacts were negligible there would be very trifling stray currents.

For example, if we are dealing with a double track of ninety-pound rail, the resistance is about $\frac{1}{606}$ ohm per thousand feet or .0087 ohm per mile. Such a structure could carry 1000 amperes with a loss of but 8.7 volts per mile and should reduce the stray currents to a very minute percentage since the resistance is not only very small compared with any probable value of the earth resistance between track and pipes, but also very small compared with the resistance of the pipes themselves including their bad joints. With, say, one per cent of the current in the earth conductors the electrolytic action, while not absolutely suppressed, would be so slow and so trifling as to be scarcely worth considering save at a few points which could be protected if necessary.

All this points to the necessity of the most perfect bonding, as before pointed out. All sorts of devices have been tried. Two of the most ingenious, aside from those already referred to, consist respectively of a plastic conducting film squeezed between the bond surface and the rail surface, and of a heavy copper dowel pin driven into a hole in the end of one rail and the other rail forced upon it and held with the fishplate. The uncertain point about these as about many other bonds is their ability to endure jarring and corrosion. Bonds are sometimes subject to the same sort of electrolytic action just mentioned in connection with pipe joints. Lately many bonds have been electrically brazed to the rails by a process closely akin to electric welding. The amount of power required is only 15 to 20 K. W. and in point of low resistance and permanence the result is exceedingly good.

The most radical cure for joint resistance of rails may be found in the two now familiar processes for making continuous rails. That a continuous rail is entirely feasible mechanically now admits of no dispute. Expansion does not and cannot take place longitudinally when rails are firmly embedded in paving, even under the extremes of temperature encountered. Whatever yielding there is, is lateral, and the track is not thrown out of line.

The electrically welded joint when carefully made is strong and reliable and of almost infinitely small resistance. The contact is non-corrodible, of great surface and so intimate as not sensibly to increase the resistance of the track. It is as far superior to a bond contact as the latter is to the contacts made through rusty fishplates. A track so excellent mechanically and electrically needs no commendation here, more than to reiterate the value of a complete and permanent connection between rails. Unfortunately the simplest form of joint which has shown ample strength is the butt welded form which requires energy to the amount of 200 H. P. or more, a quantity not often readily attainable. Recently a very good and reliable form of joint has been made by welding on a pair of fish plates at each joint the union not being over the whole surface, but at three large and heavy bosses so distributed as to make a solid and rigid joint This form of weld takes much less current than a butt weld and is amply strong.

The "cast welded" joint has now come into very considerable use. Mechanically it is superior, but electrically it is scarcely the equivalent of the welded joint. Between these two rival continuous rail processes it is difficult to choose. Certainly both afford at once the solution for the joint alignment and the bonding difficulties. The "cast welded" joint is by far the more widely used on account of its great mechanical strength and the ease with which it is made. Both are likely to come into very extensive use in large city roads where the electrolytic troubles are usually most noticable, although small roads are not exempt from them. The resistance of a cast welded joint, although not uniformly negligible, is about the same as that of the very best bonded joints and is quite as permanent.

It has often been urged that a double trolley system should be employed to avert danger of electrolytic action. Experience has shown that the double trolley is not likely to become a favorite with street railway men. It can be worked successfully with proper care, but the mechanical difficulties in the way of installing and keeping up the overhead system of frogs, crossings and the like are somewhat formidable. On a straightaway road with no branches or few the task is easier, but for the purpose in hand such roads are not the ones requiring the most serious consideration. The troubles belong especially to complicated city systems in which the difficulties of a double trolley system are something terrific. Inasmuch as every electric railway company has to pay for what can be made a magnificent return circuit, it seems totally needless to throw away the rails and operate a double metallic circuit overhead. Especially is this true in view of the fact, that considerations of track stability and durability point to the use of the continuous rail which minimizes at the same time the electrical difficulties.

It must be remembered that in long distance lines such as are found in interurban and similar work, the use of continuous rails is liable to cause trouble from insufficient resistance to expansion, as such roads generally are exposed to more violent changes of temperature. On the other hand, in the case of such roads trouble from electrolytic action is usually relatively small or entirely absent, so that bonding is sufficient. Also as will be explained later, in these roads for heavy service and rather high speed there may sometimes be good reason for using two trolleys, quite aside from all questions of good return.

Of course, when the alternating current motor is thoroughly developed for railway service much of the danger of electrolysis will be escaped, whatever the character of the return circuit, but there will still exist every reason for making the rail return as perfect as possible from motives of economy alone. For when bad bonding can increase the total resistance of the track circuit ten or a dozen times, as has happened many times, the waste of energy due to the increased drop in the circuit is burdensome.

For example, take a single track of ninety pound rail 10,000 ft. long. With continuous rails the resistance per thousand feet would be $\frac{1}{330}$ of an ohm and for the whole distance .033. With 200 amperes flowing, the drop would be 6.6 volts and the loss of energy more than one kilowatt. Now suppose each bond contact with its half of the bond wire to have a resistance of .001 ohm. On each line of rail there would be 660 of these so that the total bond resistance of the track would be .33 ohm and the drop due to this bond resistance with a current of 200 amperes would be 66 volts. The corresponding loss of energy would be 13.2 k. w. more than enough to operate an extra car. At the cost of power generally found this waste would represent in the vicinity of $1000 per year net loss, a pretty high price to pay for the privilege of having a poorly connected track, liable to cause serious trouble from stray currents. And this instance represents not at all an extremely bad case, but a very common one.

The moral of all this is that just as much care should be spent on the joints underground as on those overhead, in fact more, since the latter are but slightly liable to corrosion while the former run great risk of it. For this reason the continuous rail is doubly desirable since it not only avoids constant loss of energy in the rail joints, but averts a rather heavy cost of maintenance. With continuous rails some cross bonding may be desirable to give security against breaks, but it comes into use only in emergencies. Next to the continuous rail the best construction employs rails of some of the recent deep sections, rolled in 60 ft. lengths. These are laid with long fish plates at the joints secured with twelve heavy bolts, and are double bonded at each joint. A track so constructed has only half the usual number of joints, thus halving the usual resistance due to the bonding. These long rails are rather unwieldly as they weigh 1800 to 2000 lbs. each, but their use is very advantageous.

To prevent electrolytic destruction of neighboring conductors by stray current from the rails the best simple advice that can be given is as follows:

1. Use the continuous rail system; or

2. Bond very thoroughly; put the positive pole of the dynamo on the overhead line; join the negative directly to the track without intentional earth connection, and

3. In any case investigate the potential between track and buried conductors and run supplementary wires from these conductors to the dynamo if necessary.

This applies to small systems as well as large. The only cases which may be fairly excepted are electric roads running through country where there are no buried conductors near, and elevated roads which are really a special case of the double trolley system. As electric railways have become more common and more thoroughly understood the conditions of the return circuit have been much ameliorated, but sins against Ohm's law are still distressingly common. A feeling still seems to be rife that what is concealed from the eye may be scamped, as when the guileful wiring contractor runs underwriters' wire through the ceilings and puts okonite at the joints. It is bad enough for a dishonest contractor to do that sort of thing, but what shall we say of a man who cheats himself by doing poor work on his return circuit without even the excuse of economy.

We are now in a position to determine the quantity which was the ultimate object of this investigation into the details of the return circuit; i.e., its total net value as a conductor compared with the outgoing circuit.

This is obviously not a fixed quantity in either absolute or relative value, for even neglecting joint resistances there is far less difference between the weights of the rail used in various systems than between the weights of overhead copper. An ordinary electric road uses perhaps a rail of seventy pounds per yard. A single track so constituted is, neglecting joints, of conductivity equal to 2,200,000 c. m. of copper. If the rails were continuous it is clear enough that in a road of small or moderate size they would be perhaps ten times as good a conductor as the overhead system. This would allow for a No. 0 trolley wire and a No. 00 main feeder on the average all over the line. On the other hand, taking the resistance of bonds and joints as double that of the rail itself, the equivalent of the rail in copper falls to, say, 733,000 c. m., which is less than four times the overhead system just assumed. If this system averaged a No. 000 feeder, plus the trolley wire, it would have almost exactly three times the resistance of the track circuit.

In large systems the rails often run as high as ninety pounds per yard, so that a single track would be equal to 3,000,000 c. m. of copper. With continuous rails this full equivalent could be taken, but the feeder area plus a No. 00 trolley wire would hardly be less than 750,000 c. m., so that the resistance of the overhead wiring would be about four times that of the track. More commonly, making the same allowance for bonds as before, the track equivalent would be 1,200,000 c. m. and the trolley and feeder copper would have only about one and a half times the track resistance. Not infrequently the bonding is imperfect enough to reduce the track equivalent to 900,000 c. m., which would frequently be equaled or exceeded by the trolley and feeder copper, raising the ratio to equality. A double track, of course, improves matters. We may tabulate these results somewhat as follows, calling R^1 the track resistance and R the overhead resistance.

$R^1 = .1$ to $.2\ R$. Exceedingly good track and very light load.

$R^1 = .2$ to $.3\ R$. Good track and moderate load.

$R^1 = .4$ to $.6\ R$. Fair track, moderate load.

$R^1 = .2$ to $.3\ R$. Exceptional track and large system.

$R^1 = .3$ to $.7\ R$. Good track, large system.

$R^1 = .7$ to $1.0\ R$. Poor track, large system.

In cases now somewhat exceptional the track resistance may exceed the overhead resistance considerably. The assumption now frequently made, that the track resistance is one-quarter that of the overhead system really represents a better state of things than usually exists. To justify it requires the combination of continuous rail or exceptionally perfect bonding, with conditions of load that do not require large feeder capacity. Under the ordinary conditions $R^1 = .4\,R$ is probably nearer the truth. The proportion between R and R^1 has, of course, a very important bearing on the design of the overhead system. If the return circuit had no resistance then the entire drop

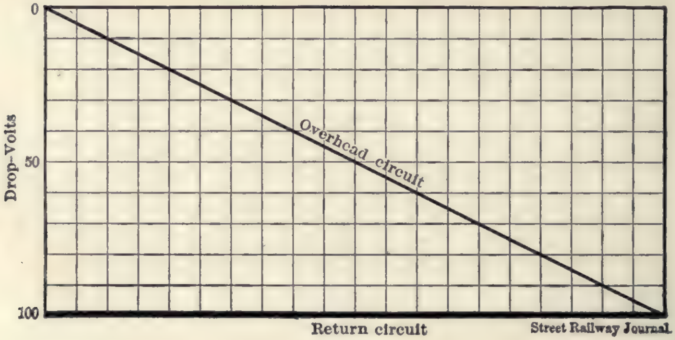
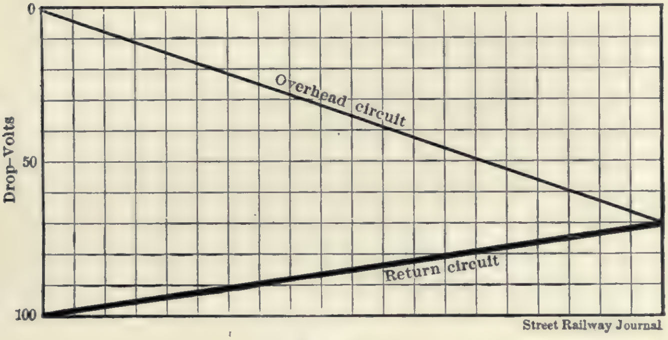


FIG. 36.

would take place in the overhead conductors and we could calculate the line for any given drop by the simple formula

$$c.\ m. = \frac{11\ C\ D}{E}$$

with D for the linear single distance. Bearing in mind however the resistance of the return circuit, it is evident that for a given total loss in volts more copper must be placed overhead than would be necessary if the return circuit were of zero resistance. In other words, if we are confronted by a considerable loss in this return circuit it is necessary to have proportionately less elsewhere in the circuit. With no resistance in the return circuit the drop in voltage may be represented graphically by Fig. 36. Here the whole drop is in the outgoing circuit which can consequently be rather small. If, on the other hand, we take the actual case in which the return circuit has a very perceptible resistance, the distribution of the drop will be as in Fig. 37, which is given by $R^1 = .43\ R$. This means that to preserve the same conditions of total loss in the circuit the overhead copper must be increased by forty-three per cent, since of the total 100 volts to be lost it is now permissible to lose but 70+ in the outgoing circuit.



Street Railway Journal

FIG. 37.

Hence to take account of loss in the return circuit the formula just given must be altered by changing the constant in accordance with the new conditions, which are there actually found in practice. The proper amount of increase in the constant is a little uncertain as is indicated by the table just given. For $R^1 = .4 R$ however the constant is 14.4 so that we may rewrite the copper formula as follows:

$$c.\ m. = \frac{14.4\ C\ D}{E}.$$

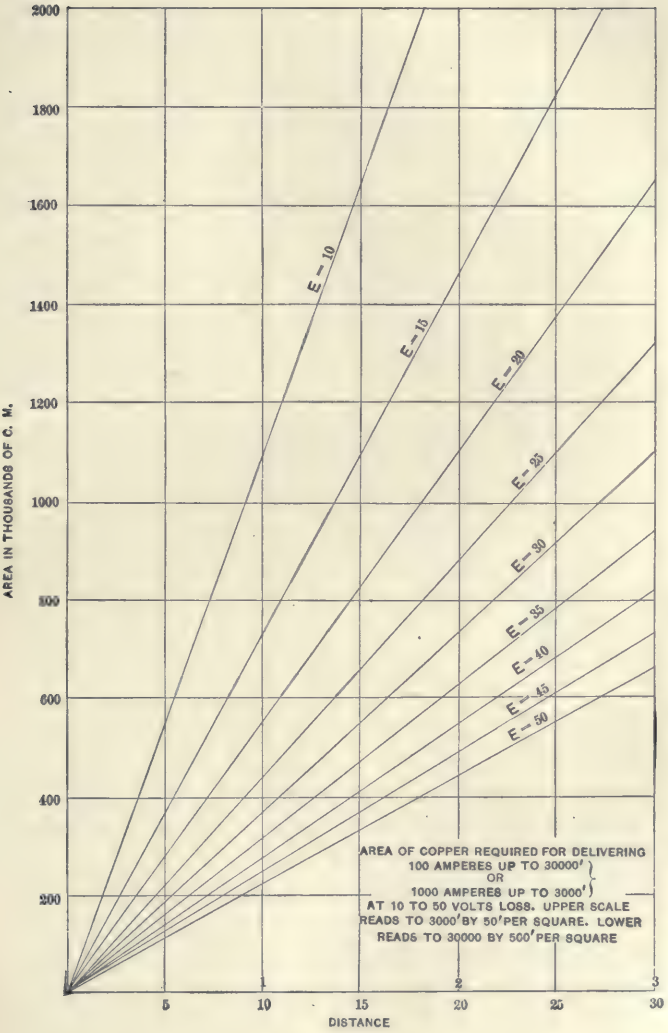
In the vast majority of cases the constant will lie between 14 and 15. The exact value to be assumed depends on the conditions as to track circuit and load in the particular case considered, and can be judged approximately from the table. It may sometimes be desirable to make a few trial calculations with different constants in order to get a clear idea of the possible amount of copper.

It is, of course, possible to determine a condition for minimum cost of the conducting system, taking account of the cost of copper, rails and bonding, but, generally speaking, the rail is fixed by purely mechanical considerations while there are, as has been shown, good reasons for making the track circuit thoroughly good. In applying the above formula, as we shall in the next chapter, it should be remembered that in extensive systems the constant may have to be modified in passing from one locality to another, for the rail conditions will probably vary and the load conditions most assuredly will change.

In cases where the track return is not used, as in double trolley and conduit roads, the outgoing and return leads may or may not be duplicates of each other. If the total drop were equally divided between them the feeder formula would of course become the familiar

$$c.\ m. = \frac{22\ C\ D}{E}$$

and the return would have the same area and total weight as the feeder system thus determined. Ordinarily there would be little advantage in making the two sides of the circuit equal and the designer would be guided mainly by



AREA OF COPPER REQUIRED FOR DELIVERING 100 AMPERES UP TO 30000′ OR 1000 AMPERES UP TO 3000′ AT 10 TO 50 VOLTS LOSS. UPPER SCALE READS TO 3000′ BY 50′ PER SQUARE. LOWER READS TO 30000 BY 500′ PER SQUARE

PLATE II.

convenience. Often the easiest procedure mechanically is to install one or more heavy return cables for o predetermined fraction of the total drop and to compute the feeder system precisely as if dealing with a track return. For the greatest economy in copper a particularly careful study of the probable distribution of the load should be made. Of course, one may divide the drop between feeder system and return in almost any convenient way, subject to the limitation imposed by danger of overheating, without affecting the economy of the distribution, but when one deals with a track return of uniform section which must be installed and paid for anyhow, there is less need of refinement than in using costly cables.

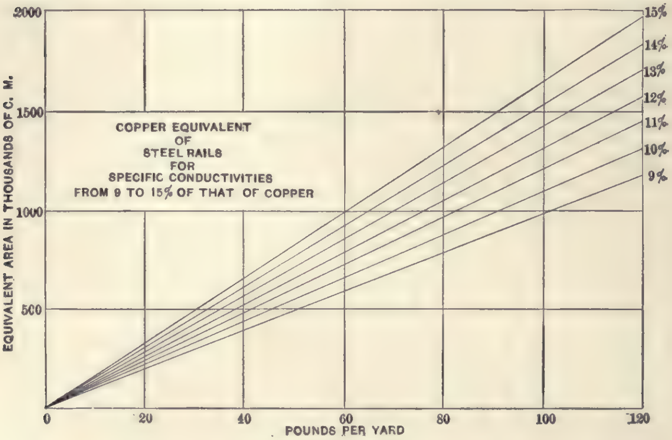


PLATE III.

Probably the best method of design in these cases is to follow the general procedure to be found in the subsequent chapters, but with close attention to the limits and variations of load in the various sections of the line, not adhering closely to anything like a track constant, but taking the data for feeders and return out of Plate II with such division of the total drop between them as seems expedient from the standpoint of simplicity in overhead or conduit construction. Plate II is merely an extension of Plate I, p. 7, arranged with reference to heavy work of this class, the abscissae being the total lengths of the wire under consideration and not the lengths of the circuits as in Plate I.

In case the working conductors are of other material than copper they should be reduced to the equivalent section of copper. For this purpose Plate III, developed from Fig. 17, p. 30, will be found convenient in all computations involving rails or other iron or steel conductors.

Third rail systems with ordinary track return may or may not involve supplementary feeders. Plates II and III will enable these cases to be easily computed, once the loads are determined.

CHAPTER III.

DIRECT FEEDING SYSTEMS.

By direct feeding is meant the supply of current to the working system of conductors from a single central station, without any intermediary apparatus. It is the system employed on most present electric street railroads, save a few of the largest size. It is ordinarily used on interurban lines and would be universally applied were there not many cases in which the distribution of power from a single station becomes uneconomical at any practicable voltage on account of the great distances involved.

Nearly all interurban lines, and especially the systems which are likely to result from the conversion of steam into electric lines, can be best operated by other means which will be described in subsequent chapters. Indeed a careful examination of very many existing electric railways will disclose the fact that direct feeding is being worked far beyond its proper limits of application and is the cause of serious pecuniary loss, both in interest on a huge investment in copper and in power needlessly lost on the line.

Direct feeding however is properly applied in most instances, and must be ultimately applied as the distributing system almost universally, since even where substations are employed the lines proceeding from them are often a case of direct feeding and must be treated as such.

Electric railway feeding systems are akin in principle to those employed in simple cases of distribution for lighting, and yet in practice differ from them very radically in certain particulars. Railway feeders are not generally designed to preserve uniform voltage within the area fed, but to hold the voltage, admittedly variable, within certain rather wide, but fixed limits. Lighting feeders must be designed with reference to a load varying in the same area from time to time, but yet closely confined to that area; railway feeders must be so designed as to meet not only a load variable in amount from second to second, but shifting from place to place obedient to causes that follow no definite law. On the other hand not only are railway feeders absolved from the necessity of holding the voltage closely uniform, but by virtue of this they can the more easily be arranged to meet extreme shifting of the load.

In early electric railways the trolley wire proper was rather small and the feeding was often relatively quite as complex as that in large modern systems.

The conditions which must be met in planning a direct feeding system are roughly as follows:

1. The maximum fall in voltage at any point in the system under all working conditions must not exceed a fixed amount.

2. The average drop throughout the system under normal conditions must equal a certain predetermined amount.

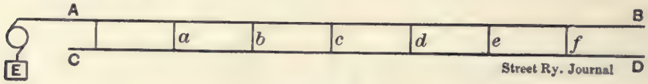
3. The feeders must be so connected that accidents to the working conductors shall interfere with traffic to as small an extent as possible.

To meet these various conditions a large number of arrangements of feeders have been devised, many of which are in extensive use. The following are some of the most usual, which have stood the test of experience.

1. The so-called ladder system shown in Fig. 38. Here one pole of the dynamo is earthed as usual and the other is connected to the trolley wire C D, and also to the feeder A B. These are connected at intervals of a few hundred feet by subfeeders *a*, *b*, *c*, *d*, *e*, *f*, etc., which are generally hardly more than tie wires uniting the principal feeder to the trolley wire. This arrangement was very common in early electric roads. It made possible the use of a very slender trolley wire merely large enough to carry conveniently the current for cars running between the subfeeders, and made the system tolerably free from interruption by accidents to the trolley wire, which from its small size was

rather prone to break. Both the trolley wire and the principal feeder are continuous and of uniform cross section. This continuity is useful in case of the crowding of cars at one or more points on the line since it brings to the rescue the full conductivity of the system. It is bad however in case of short circuits in that the main circuit breaker at the station is quite likely to open and stop every car on the line.

As a real feeding system it hardly deserves the name, since electrically it is nothing more than a continuous working conductor of uniform area. The properties of such a conductor have already been fully considered in Chap. 1. The only additional fact that has to be taken into account in the ladder system is the limited conductivity of the trolley wire between the subfeeders. The drop in voltage at a car located at any point is practically the drop in the principal feeder up to that point plus the drop in the trolley wire from the car to the nearest subfeeders, which are virtually in parallel, inasmuch as current flows into the trolley in both directions along the trolley wire.



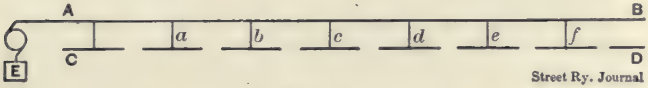
Street Ry. Journal

FIG. 38.

2. A system similar in some respects to Fig. 38 is shown in Fig. 39. Here there is as before a principal feeder A B. The trolley wire C D is not however continuous, but is broken by insulating joints into separate sections of approximately equal length each with its own subfeeder *a*, *b*, *c*, etc. The added conductivity of the continuous trolley wire is, of course, sacrificed by this arrangement. Both the trolley and feeder are generally of uniform area throughout their respective lengths and the system is electrically, to all intents and purposes, a uniform linear conductor save for the abrupt change in conductivity in passing from the principal feeder to any subfeeder and its section of trolley wire. As regards a load at any point

the total drop is that in the principal feeder up to the subfeeder controlling the section in question plus the drop in the subfeeder and the trolley wire up to the load.

The advantage gained by cutting the trolley wire into short, independent sections is a certain amount of immunity from breakdowns. The subfeeders *a*, *b*, *c*, etc., are usually provided with fuses or switches or both, so that while in case of a break in the trolley wire the cars on the adjacent sections are not deprived of current any more than in the ladder system, there is no longer the danger of stopping traffic by blowing fuses at the station, since the subfeeder fuse immediately acts to stop an excessive flow of current. In addition, in case of fire or flood affecting any part of the system, the disturbed region can be very promptly isolated by opening the circuit at the subfeeders. In cities where fires are of frequent occurrence such an arrangement is highly necessary, although it is generally desirable to use a far more complete feeding system in connection with it. Both the arrangements just shown are entirely without special provisions for holding up the voltage at distant parts of the line, depending practically on the conductivity of the principal feeder.

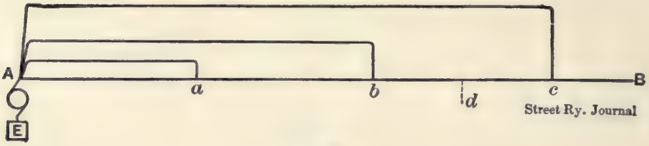


Street Ry. Journal

FIG. 39.

3. A true feeding system corresponding in a general way with Fig. 38 is shown in Fig. 40. Here A B is the trolley wire while in multiple with it are feed wires tapped into the trolley wire at *a*, *b* and *c*. These feeders are generally quite independent of each other up to their respective junctions with the trolley wire. A load at any point, as *d*, receives its current in both directions through the trolley wire, which in turn draws current from the adjacent feeders. The conductivity available at the load *d* is that of the trolley wire from A to *d*, reinforced by the feeders *a* and *b*; in parallel with that of the trolley wire section

from *d* to *c* and the feeder *c*. With the arrangement of Fig. 40 it is quite possible to hold the voltage fairly uniform by giving sufficient area to the longer feeders. As a matter of convenience, to avoid the undue multiplication of wires, the distances A *a*, *a b*, etc., between feeders are made considerably longer than in the ladder system: hence the trolley wire is generally larger. Of course, it must be large enough to avoid excessive drop in the sections *b d* and *c d* when load is applied at *d*. As a rule the distances A *a*, *a b*, etc., are several thousand feet except where the traffic is very heavy. With No. 0 or No. 00 trolley wire the distance named is not generally excessive. As compared with the ladder distribution this one has the great advantage of giving a fairly uniform voltage, and can be more readily arranged to handle abnormal loads at distant parts of the line. It has also the same convenient property of giving current to each car from two directions so as to minimize the effect of breaks in the trolley wire. It is however exposed to trouble in case of serious short circuits, and is inconvenient in the matter of cutting out portions to execute considerable changes in wiring or to avert accident.



Street Ry. Journal

FIG. 40.

4. An obvious modification of the arrangement just mentioned is that shown in Fig. 41. This bears the same relation to (3) that (2) does to (1). It shares with (3) the advantage of maintaining fairly constant voltage under normal conditions, though it is somewhat at a disadvantage in case of a heavy load on a distant section, since that section must depend on its own feeder alone without assistance from adjacent sections. The feeders *a*, *b*, *c*, etc., are provided with individual switches and cut-outs at the station so that if a short circuit occurs nothing worse can happen

than the temporary disabling of that particular section, while if necessity demands any section can be promptly cut out of circuit in case of fire along the line or any other sufficient cause. (4) is very well adapted for use on long lines with fairly regular traffic. Like (3) it requires a rather heavy trolley wire for the best results. A load at any point is supplied by the feeder for that section in series with the trolley wire between the load and the feeder junction, so that the drop under any given conditions is very readily computed.

In both (3) and (4) it is sometimes convenient to tie two or more feeders together, as shown by the dotted line at *d* (Fig. 41). This procedure reinforces the conductivity with reference to the section thus connected, as *b*, and while it may lower the voltage of sections beyond the link, is very useful when a particular section is exposed to severe loads from grades or massing of cars, particularly since such linking can be applied at any time that the service may require it.

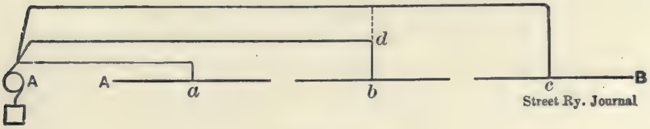
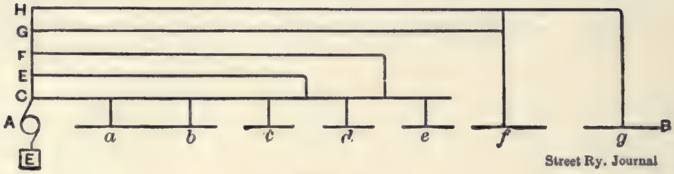


FIG. 41.

In very many cases it is advantageous to install a composite feeding system which can be made in a considerable measure to unite the advantages of those already described. A very useful combination is that shown in Fig. 42.

Here the trolley wire, A B, is cut into sections of varying length, short where considerable danger of interruption of service exists, long where longer sections can be more conveniently utilized. C is a principal feeder as in the ladder system connected at *a* and *b* to a continuous trolley line, and at *c*, *d* and *e* to trolley sections. This principal feeder is reinforced by feeders E and F to equalize the voltage more perfectly in the region of dense traffic, while the independent feeeders, G and H, supply the long isolated sections, *f* and *g*. G and H are moreover linked at *f* if the conditions of service require. Fig. 42 represents the actual arrangement of an extensive feeding system much more closely than any of the simpler arrangements shown. As a matter of fact such a complex system is generally the outgrowth of the conditions which develop in service rather than the result of deliberate forethought. Nevertheless, good engineering often demands the adoption of such apparently complex methods.

In general, independent feeders are necessary to preserve good working pressure in outlying districts where comparatively independent lines are worked, while in regions of dense traffic the tendency is to link together the principal feeders of neighboring lines into a network reinforced by special feeders wherever necessary. The trolley wire is sectionalized only in so far as danger from fires and electrical troubles require. Although a continuous trolley wire is now far less necessary than formerly on account of improved methods of construction, on the other hand an extensive subdivision into sections hinders the full use of all the copper installed and increases the danger of local stoppage of traffic. On any railway system, street or other, continuity of service is of the first importance, both by reason of the direct loss from suspension of traffic and the indirect, but far more serious, loss of public confidence and goodwill.



Street Ry. Journal

FIG. 42.

Consequently it is often advisable to take chances in order to keep running, and linking feeders and trolley into a continuous system to drive through a time of short circuit if possible rather than shut down part of the system. The present tendency is to make the various sections of feeders and trolley wire separable rather than separate, so that they can be cut apart when absolutely necessary, but not long before that crisis.

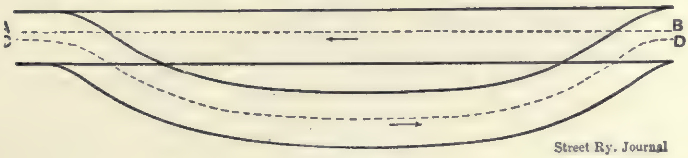
Long lines, interurban and the like, may often be best treated indirectly through substations, but when direct feeding is employed, it is ordinarily best to use a very substantial trolley wire, not smaller than No. 00, installed in separable but not disconnected sections, and supplied with current by separate feeders, which may be linked if local conditions require. If large power units are to be employed, requiring large currents, it is better to use a very large trolley wire than to install a principal feeder, since with large currents the larger the contact surface of the working conductor the better, and the conductivity of the trolley wire can be relieved if insufficient by connecting each section to its feeder in several places instead of one. There is no reason however why, on large work such as is found in converting steam roads to electric, the working conductor may not have a cross section equivalent to No. 0000 wire or more which enables comparatively long sections between feeders to be employed with advantage. For example, suppose a No. 0000 trolley wire carrying a current of 200 amperes per section received equally from the two adjacent feeders. This condition would be met by a train requiring one hundred kilowatts to drive and located midway between two feeders. Allowing no more than two per cent loss, i. e., about ten volts in the trolley wire between feeder junction and load and substituting the above values in the fundamental equation $c.\ m. = \frac{11\,C\,L}{E}$, the distance between feeders should be about 4000 ft. Inasmuch as the average drop produced by the moving train, with a maximum of two per cent midway between feeders, would be but one per cent, it would generally be advisable to increase this amount. Allowing an *average* drop of two per cent in the trolley wire, i. e., a maximum of four per cent, the proper distance between feeders would be virtually doubled, rising to about 8000 ft.—a mile and a half.

For long roads, then, one may use with advantage such an arrangement of feeders as is shown in Fig. 43.

Here a continuous heavy trolley wire is divided into sections of, say, a mile to a mile and a half in length, each with a junction to the feeding system. This, as shown, consists of three main feeders, each supplying two sections of trolley wire. The number of these main feeders and the number of sections each supplies is regulated by convenience and local conditions, as is too the length of each section. The sketch (Fig. 43) shows merely the principle, which is well suited to roads up to a dozen miles in length fed from somewhere near the middle. Such roads are apt to require rather large units of loads, due to well loaded trains and high speed, but the number of trains to be operated at any one time is usually small. A rather nice question sometimes arises as to the relative cross section of copper to be put in the trolley wire and in the feeders. In the large work that we are just now considering, the trolley wire must be in any event large enough to give sufficient contact with the trolley. And this is apt to indicate about as large a working conductor as can conveniently and securely be supported. Therefore the feeders will be relatively smaller than in ordinary street railway practice, and it is not advantageous to separate permanently the sections of trolley wire, thus throwing away the conductivity of its large cross section. Whenever double tracks are used it goes quite without saying that the whole system of conductors should be united, each trolley wire serving as a feeder to the other.

FIG. 43.

Occasionally, too, on single track roads with frequent turnouts, two trolley wires are strung ten or twelve inches apart, each to accommodate the cars running in one direction, so as to entirely avoid overhead switches of any kind. This arrangement is shown in Fig. 44, and while it is not now very widely used, it is exceedingly convenient in certain cases. In Fig. 44 the track at a turnout is shown by the solid lines and the two trolley wires by dotted lines. The trolley wire, A B, would naturally be used by cars running from right to left as indicated by the arrow, while C D would be used by cars running from left to right. Each car keeps to its own trolley wire throughout the track, unless it is necessary to change over in backing around a turnout. This double trolley device enables long extensions to be handled without feeders.



Street Ry. Journal

FIG. 44.

Before passing to the actual computation of a trolley and feeder system, we must go back to our two fundamental propositions and inquire into the permissible maximum drop and what we mean by average drop.

Suppose that ten per cent average drop has been decided upon in a given case,—What is really meant by this? There has been considerable confusion on this point. Are we to understand that this average drop is that determined from the effect of the maximum working load throughout the system, or is it the average loss on the parts of the system considered separately irrespective of their relative amounts. Is it the drop produced by the average load or the average of the drops produced by the simultaneous loads at some particular time?

To reduce the matter to a common basis with other cases of the electrical transmission of energy, we are at liberty to put but one interpretation upon average drop. By it we should mean in every case that a certain specified proportion of the energy delivered to the line during a particular period is to be lost in the transmission. On this basis we can design the system for conditions of maximum economy, knowing approximately the probable cost of energy per kilowatt hour and the price of copper. Starting with this definition, we can then intelligently work out the relation of this average energy loss to the loss in volts at the various parts of the system. It is necessary however to bear in mind, first, that the same conditions of economy with respect to loss in transmission do not necessarily hold for all parts of a given system, and second, the question of economy in transmission is quite subordinate to that of successful operation.

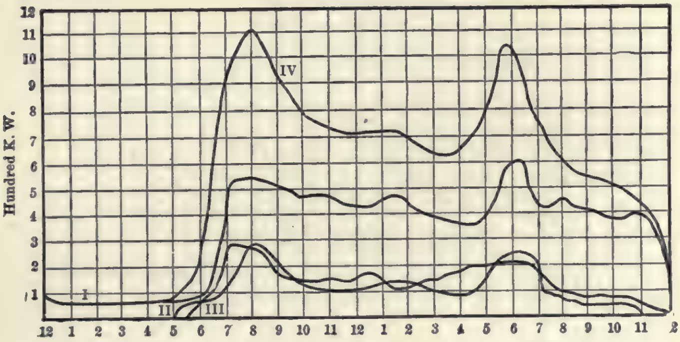
As regards the former consideration, the average energy delivered to an electric railway system is a very different thing from either the maximum energy or the average energy during the hours of heavy load. The load factor, i. e., the ratio between average and maximum output on a railway system is generally rather unsatisfactory, as has already been indicated. It ranges in general from .3 to .6, varying greatly with the size of the system, the character of the service and the habits of the people who ride. In cities many interesting facts appear from the load curve of an electric railway—the movements of workingmen, the crowd of shoppers going downtown in the forenoon, the migration in the early afternoon, the homegoing at six and the theatre crowd an hour and a half later. All these factors of load operate with varying force, not only in different places, but in different parts of the same system. The changes from day to day are considerable, but on the whole the same line preserves its character remarkably well. The result of a varying load factor is a necessary limitation in the permissible loss of energy. For if we have a load factor of .3, the average loss of energy, whatever economy of transmission may indicate must not be enough to cause at maximum load a drop in voltage sufficient to interfere with the proper operation of the cars. If we write for the maximum permissible drop, V, v for the drop corresponding to the loss of energy for greatest economy of transmission, for the load factor, L, and for the drop assumed, V^1, we have the following inequality which sets a limit of drop which must not be exceeded

$$V^1 < L\,V$$

Very fortunately it usually happens that

$$v < L\,V$$

so that there is no special difficulty in making $V^1 = v$. But it is not safe to assume this happy condition of things without some investigation. It may be true of one part of the system and not of another. It is necessary therefore to look into the various parts separately in laying out any considerable system. Fig. 45 shows three load curves which may be supposed to be from three parts of the same system, together with the summation curve of the three from which the total load factor would be determined. I may be taken as the load curve of a main urban system, while curves II and III will serve for branches. IV is the summation curve of the whole. The load factor of this final curve is very evidently worse than that of the main line, curve I, since heavy loads in morning and evening on branches II and III raise the morning and evening maximum values



Stre t Ry. Journal

FIG. 45.

on IV. The load factor of II is hardly better than .3 while that of I is nearly .6. Consequently we have far less latitude in planning the conductors for this branch than in case of the main line, being always confronted by a high maximum to be taken care of. The load factor however does not fully represent the precautions that have to be taken. It shows, to be sure, the normal maxima, but it does not include the effect of shifting load.

This is really a very serious matter in making the plans for a conducting system and the probabilities of the case need to be carefully weighed. A base ball park, for instance, located far out on a branch line means trouble unless it be taken into account. It means that now and then, not only all the regular cars on the line, but all the extras that can be spared, will be massed at or near the distant end of the branch and brought in heavily loaded and all together. It is the same effect that would be obtained from a steep grade, except that it is only occasional. The amount of such an extra load may be sufficient to double the ordinary maximum load and that in the most disadvantageous place, i. e., at the end of the line. From what has been said it is sufficiently evident that laying out the conductors for a large system is more a matter of acute judgment than of exact theory.

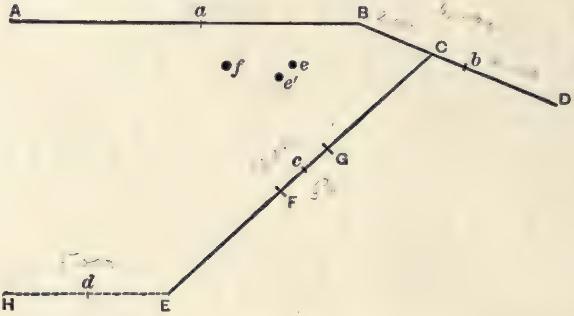


FIG. 46.

The reason for this is that there are no data sufficient to justify a general theory based upon them. The value of the load on an electric railway is so uncertain, whether for any stated time or during any interval, and so uncertain in position as well as amount, that the success of any calculation depends almost wholly on the skill with which the data are assumed.

A convenient way of entering upon the calculation of a conducting system is to take up the data involved in the following consecutive steps.

1. Extent of lines.
2. Average load on each line.
3. Center of distribution.
4. Maximum loads.
5. Trolley wire and track return.
6. General feeding system.
7. Reinforcement at special points.

The first two steps are necessary preliminaries to the third. The fourth determines the permissible drop, the fifth gives the division of the overhead copper between trolley and feeders, and the allowance that must be made for the resistance of the return circuit. The sixth stage is the preliminary calculation of the conductors and the seventh the modification of this to take full account of local conditions. The application of the whole process is best shown by working out an hypothetical system in detail, step by step. Two cases may properly be taken up; first a regular street railway system, and second, an interurban line of moderate length.

Suppose a new system is to be installed or an old one reorganized of which the track is shown in the simple chart (Fig. 46). Here the main line, A B C D, is double track throughout. A B is 10,000 ft., B C 2000 and C D 4000, making a total length of 16,000 ft. At B C the main line is joined by the single track branch, C E, 10,000 ft. long, on which at F G is a five per cent grade 2000 ft. long.

Step 1. Lay out the track to scale, noting the different distances carefully and the extent and position of grades. The scale need not be large, say, an inch to the thousand feet, and a couple of tracings of the chart will prove convenient. If any extensions are contemplated, as at E H, dot them in as they will enter into subsequent calculations. As shown, E H is supposed to be 5000 ft. Now divide the road into sections so that in each one of them the service shall be under ordinary conditions fairly constant. For example, the main double track would present tolerably uniform conditions throughout and could be considered as a single section. Owing to the change in direction at B, however, which might conceivably affect the location of the power station, it is better to take A B as one section and B D as a separate one. C E, the long single track branch, will naturally form a third section; while H E may be taken tentatively as a fourth.

Step 2. Now as to the loads upon each section. The number of cars on a road, of course, depends entirely on the traffic. With the advantage of a good population to draw upon, such a line as we are considering might operate as many as twenty motor cars. These would naturally be sixteen or eighteen foot single truck cars, probably the latter. We may then assume, say, ten such cars on section A B, six on B D and four on C E. Those on C E in the natural course of events would run quite independently, simply serving their own line. We can then assume as the total load twenty eighteen foot cars, each equipped with a pair of standard motors, such as are usually rated at twenty-five horse power each. The power required to operate these cars is, of course, exceedingly dependent on the density of the traffic. So long however as the cars are equally loaded the center of gravity of the system is quite independent of the absolute amount of horse power required for each car. Recurring now to the theorems regarding center of gravity in Chap. I, we are in a position to determine the best position for the power station. The only question to be first decided is what is to be done with respect to the proposed extension. If it is installed as an extension of C E, probably two additional cars would be needed.

Step 3. As the service on each section is uniform the load can be considered as concentrated at the middle point of each section. Determining the center of gravity of the three existing sections by Fig. 47, constructed like Fig. 10, we find this center at *e*. Combining with this the effect of the proposed extension, it appears that the addition of this extra load would shift the center of gravity to e^1, a distance of somewhat less than 500 ft. Transferring these points to Fig. 46 we have the theoretical location for the power station.

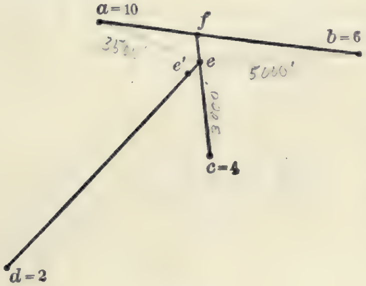


FIG. 47.

Its practical location is, however, a very different matter. Very many things besides cost of copper for distribution enter into the problem. In the first place *e* may fall in a locality in which real estate is very valuable, so that it will pay to shift the center of distribution a considerable distance rather than endure the cost of a site for the power station at *e*. Again *e* may be inconvenient with respect to coal and water supply. The cost of carting coal or pumping the water for condensation purposes may very easily outweigh the saving in copper due to distributing from the theoretical point. It will perhaps be found that there is a considerable region within which the station can profitably be shifted to obtain cheap land, coal and water. It is not difficult to form an idea of the extent of this region. To do so, however, we need an approximate idea of the cost of copper for distributing the necessary power from the point *e*. This is very quickly obtained. We can consider a load of 18 ~~sixteen~~ cars as concentrated at *a* (Fig. 47). This is approximately 3500 ft. from *e*. Similarly six cars are at *b*, 5000 ft., and four cars at *c*, 3000 ft. We have seen in studying Fig. 10 that the total weight of copper required for such a system is

E 30

C = amperes = 20 per car

l = distance one way = $\frac{1}{2}$

$$\Sigma W = K \Sigma c l^2.$$

Remembering that we are considering feed wire alone, since the trolley wire is fixed in location, we may assume a reasonable drop in voltage of, say, thirty volts. K above then becomes $\frac{33}{30}$.

Forming the above summation we have at twenty amperes per car,

cars C amps l^2

3500 L = 3.5 3.5^2 = 12.25

$$\Sigma W = (10 \times 20 \times 12.25 + 6 \times 20 \times 25 + 4 \times 20 \times 9)\tfrac{33}{30} = 6787 \text{ lbs.}$$

Now at fifteen cents per pound this feeder copper would cost just about \$1000. For any other point than *e* the cost will be greater by varying amounts and the increase is about the same for all points equidistant from *e*. As the weight of copper varies with the squares of the distances, the mean distance of the load with respect to weight of copper is determined by

$$L^2 C = \Sigma l^2 c = 6170 \quad \text{where } C = \Sigma c = 400$$

Hence L = 3950 ft. nearly. This distance is the radius of the circle about which the station can be shifted without more than doubling the cost of copper noted above. That is, the station can be located anywhere within about three-quarters of a mile of the center of gravity of the system without increasing the cost of copper more than \$1000. Such figures are necessarily approximate only, since in practice wires cannot be run in straight lines, but have to follow the streets, nevertheless they give valuable information.

A brief examination of proposed sites for the power house will generally disclose that which is most advantageous with respect to coal and water, and a quick summation as above will tell quite nearly whether the extra copper will cost too much or not. In the case before us we will assume the point *f* (Fig. 46) as best meeting all the requirements. As the distance $e e^1$ is small compared with the displacement of *f*, we can let the extension question take care of itself and are ready to proceed to

Step 4. The predetermination of the maximum or average load is no easy matter, yet upon it depends the proper design of the conducting system. It is not difficult to estimate with a fair degree of accuracy the actual power which must be supplied to drive a car of assumed weight over a certain line at a given speed. But what the real weight of the loaded car will be, and what the condition of the line will be is a case at best for educated guessing. Roughly speaking the power required at the car wheel for a speed of eight miles per hour is .4 h. p. per ton, plus .4 h. p. per ton for each per cent of grade. More exactly

$$P = W\,(.43 + .43\,G)$$

Wherein G is the per cent grade, W the weight of car and contents in tons and P the total horse power. This assumes a straight track and a tractive effort of twenty pounds per ton on the level. But there are always some curves, the speed is often above eight miles per hour and at low speeds the motors are somewhat less efficient than at high speeds. Allowing a complete efficiency of two-thirds from trolley to car wheel and assuming a pressure at the car of about 500 volts we shall not go far wrong in reckoning 1¼ amperes per ton of car *plus* 1¼ amperes per ton for each per cent of grade. This average indicates an average of about fifteen amperes per car. The average current taken while the car is under full headway will frequently exceed this amount, but an allowance of fifteen amperes average throughout the hours of running will generally be nearly right for a road such as that under consideration. With long double truck cars the average current will rise to about twenty-five amperes.*

Now the maximum current must be considered. On large systems it may be no more than twice the average. As the number of cars becomes smaller this ratio increases. With one or two cars it is no uncommon thing to find maximum currents of four or five times the average. Still larger ratios would be common if the same speed were maintained on grades as on the level

---

*A good average rule for power is 100 watt hours per ton of car per mile of schedule speed per hour.

portion of the track. We can now go back to Fig. 46 and form a tolerably clear idea of the current to be furnished. On section 1, A B, we may fairly count on a normal load of 150 amperes, rising to occasional maxima of, say, 450 amperes. On section 2, preserving about the same ratio since it is really a continuation of section 1, we may expect about 90 amperes average and 270 maximum. On section 3 with four cars the average would be about 60 amperes and the maximum about 150 amperes. These figures however do not tell the whole story, for they give no clue to the points at which the maximum currents must be furnished. This matter depends, of course, on local conditions. On sections 1 and 2 it is quite within the range of possibility to have all the cars on either track piled up at either end of the line under unfavorable conditions. We should then be prepared for handling a load of not less than half the maximum at the ends of the sections, and preferably more than this. On a very large system it is quite out of the question for all the maximum load to be concentrated at one end of the line, but on a small road there is a much greater chance of such a contingency. It certainly would not be safe to allow for less than 300 amperes at the ends of section 1, and about 250 on section 2.

With section 3 the case may be still different. Suppose we have a base ball park at E (Fig. 46). To handle the crowds comfortably or at all would probably require massing about E fully double the normal number of cars on the branch and having them all heavily loaded at once, and what is worse starting them all about the same time. 300 amperes is little enough to allow even with careful handling of the cars with respect to starting.

We may now tabulate our currents about as follows:

	Sect. 1	Sect. 2	Sect. 3.
Average	150	90	60
Normal maximum	450	270	150
Extraordinary maximum at end of section	300	250	300

The maximum for the whole road would probably seldom or never exceed 750 amperes, since the conditions which produce maximum loads seldom operate all over the system at once.

With these data we can attack the feeder problem after deciding on the amount of copper to be put into the trolley wire and the value to be assigned to the track return.

Step 5. How large ought the trolley wire to be? The answer to this question must be somewhat empirical, but we can get a line on it by considering the currents it has to carry. Adopting the ladder system of Fig. 38 a very small trolley wire would answer. But we have seen that this arrangement is of little service in equalizing the voltage along the line, and hence it is better on the whole to use the system of Fig. 41 or some modification of it. To avoid running an inconvenient number of feeders it is then desirable to install a trolley wire big enough to carry current for the service of a considerable distance. Referring now to Plate 1, page ~~8~~7, we see that allowing a drop of five per cent, i. e., twenty-five volts, in the trolley wire, all that should generally be tolerated at normal load, we can get reasonably long distances between feeding points, say 3000 ft. or more, by using No. 0 or larger. No. 00 is a standard size and gives rather better service than No. 0 in case of considerable load being bunched at one spot. Assuming this as the trolley wire, we may pass to the track return. The general principles of this have been very fully discussed in Chap. II. The only thing needful here is to judge from the general conditions the value to be assigned to the conductivity of the track as compared with that of the overhead system. In the present case we are probably dealing with sixty to seventy pound rails and the main line is double tracked. The bonding is, or should be made, good, and since the total service is not heavy the track conductivity is of the better class. It is probable therefore that raising the constant of equation 3, Chap. I, to 13 will fully take account of the return. Were the service even lighter or the rails continuous we might be justified in assuming 12, while with poor bonding and heavy traffic it might be necessary to assume 14.

Step 6. Approximate data are now at hand for laying out the feeding system proper. We may start with a duplicate of Fig. 46, as Fig. 48, showing now only the actual lines and H, the location of the station. From A to D there are two No. 00 trolley wires, one for each track. From C to E there is one such trolley wire. We may now find more exactly the proper distance between feeders. Beginning with section 1, we find that in regular traffic each trolley wire will supply five cars at various points. Now going back to equation 2, substituting our new constant and transposing we have

$$L = \frac{c.\ m.\ E}{13\ C}.$$

assumed drop

= 15 amps = 1 car

Here $c.\ m. = 133{,}000$, $E = 25$, and $13\ C = 195$. L therefore equals for a single car very nearly 17,000 ft., for two cars 8500 ft., for three cars 5666, for four cars 4250, and for five cars 3400 ft. Hence a single feeder at the middle point of A B would be sufficient to handle the average load uniformly distributed, very nicely. The same is obviously true of sections B D and C E. Just here appears the peculiar characteristic of railway systems—the unpleasantly large maximum loads. If the load at the end of A B should be 300 amperes as we have supposed, i. e., 150 amperes to be supplied by each trolley wire, the corresponding drop in volts would be by equation 3

$$E = \frac{13\ C\ L}{c.\ m.} = 73 + .$$

Which in addition to the loss in the feeder would produce a total drop which would be decidedly troublesome, although hardly enough to cause serious difficulty. The cars would run, but the motors would heat badly and it would be difficult to make time. On B D the conditions would be better, but with the maximum load at E the drop would be enough to stall the cars completely and they would have to be slowly worked away one at a time.

As to the effect of drop, with the usual 500 volt motors, a drop of 75 to 100 volts is decidedly annoying compelling the motors to slow down and work inefficiently, while if the drop reaches 125 volts or more the motors are nearly inoperative under heavy loads, although they will still work if too great demands are not put upon them. It is highly undesirable to deal with more than 100 volts loss under maximum load in a 500 volt system. By overcompounding the generators these conditions can be much relieved. With the maximum drop limited to twenty per cent, it is clear that the average drop, with the ordinary ratios between average and maximum load would have to be limited to five or at the utmost ten per cent.

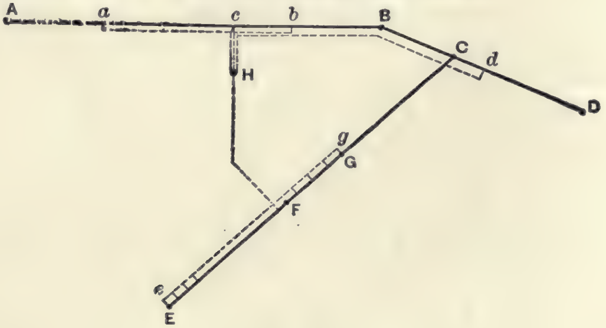


FIG. 48.

If the dynamo be overcompounded, as it should be for at least the average drop, then the maximum drop will generally fall within safe limits. It is a common practice to overcompound ten per cent, i. e., fifty volts, so that even a total drop of twenty-five per cent will still leave the system in fair operative condition.

Coming back now to Fig. 48, we have found that the system is operative at average load by means of the trolley wire alone, but should be well re-enforced by feeders to meet the conditions of heavy load. Since we have found that feeding at the middle point of A B would give too much drop even if the loss in the feeder were as small as five per cent at average load, the next step is to feed at two points. These should be so chosen, if the load is uniform along the section, as to be one-half the length of the section apart. *a* and *b* (Fig. 48) have this position. No load can therefore be more than 2500 ft. from a feeder. Now consider the maximum load of 300 amperes at A. Suppose first that the feeder H *a* is to give five per cent drop, twenty-five volts at average load. This average (half the total average load) is seventy-five amperes. The distance A H is 4500 ft., the wire therefore must be of area,

$$c.\,m. = \frac{13 \times 75 \times 4500}{25} = 175{,}500.$$

This is best met by a No. 000 wire, which is the nearest size (167,000 c. m.) and will give less than one per cent more drop.

With 300 amperes at A the drop in the trolley wires for 2500 ft. would be thirty six volts. The drop in the feeder would obviously be a little over a hundred volts, making a total quite too great, since the overcompounding, unless a special generator be devoted to the feeder in question responds to the total load on the system and not fully to the load at A. Even the gain from the current path along H B *a* will not relieve matters quite enough. Now we might use a much larger feeder and thus reduce the drop, but a simpler and cheaper way is to cross tie both feeders into the trolley lines at *c*. This, assuming both feeders to be of the same size, puts at our disposal from *a* to *c* no less than 433,000 c. m., with 334,000 c. m. for the 1000 ft. between H and C. The total drop will then be $36 + 31 + 12 = 79$ less whatever has been gained from the overcompounding. This last depends on the total load on the system and is consequently indeterminate. It could hardly however be less than half the full overcompounding, say twenty-five volts, thus giving a net drop of fifty-four volts at A.

This cross connecting process is a very useful safeguard against extreme terminal loads, though if the whole line is likely to have a heavy distributed load at the same time, it is better to take a different step as will presently be shown.

Obviously a maximum load at B will produce no trouble, so that we may pass to the section B D. If this be fed in the middle at *d* the loss in the trolley wire at average load is very trifling, not more than that due to the current for two cars over each trolley wire at a distance of 3000 ft.—about nine volts. So far then as average loss is concerned we could properly allot to the feeder carrying ninety amperes a loss of forty-one volts. If B D and A B are connected at B we can get considerable relief in ordinary states of load. The worst possible load would be 300 amperes at B and 250 at D. The drop in B D would then be thirty-six volts. Since with such a compound load the overcompounding would be up to its full amount, we can allow eighty to ninety volts loss between *d* and the station. If this were all in the feeder H *d*, it would have to be of about 288,000 c. m. But on account of the overcompounding we can get material aid from the main line up to B, and so will try to make a No. 0000 (211,000 c. m.) answer the purpose. If the line via B can be counted on for, say, seventy amperes, the No. 0000 will take the rest. With 370 amperes the drop from H to B is about 40 + 45 volts in H *c b* and B *b* respectively, less the over compounding, while the loss in B *d* would be nominal. In fact a glance at these figures shows that a No. 000 will do admirably, for our line via B can evidently furnish considerably more than seventy amperes without too much loss.

This settles the first two sections. As to the third, it is evident at a glance that it cannot be fed in the middle point since A B with two trolley wires could not be so fed, while C E has only one. Therefore a feeder should be run by the shortest route from the station to C E and then along the line to E, for 300 amperes is too much to carry over a No. 00 trolley wire, and that load must be dealt with at E. Let H *e* be this feeder, 8000 ft. long, 4000 ft. being along the line. Now if we could depend on stiff overcompounding to help us out at E, these feeders could be quite moderate in size. As it is however the chances are that the load on other parts of the system would be rather small when the maximum load is to be met at E. Therefore it is not safe to count on more than twenty or twenty-five volts help from this source. Bearing this in mind the first thought would be to try the No. 000 that served for a similar load at A. From F to E we have a No. 000 plus the trolley wire, i.e., 300,000 c. m. The drop over this line would then be fifty-two volts. It is clear from this that to come within decent limits there must be extra feeder capacity from H to F. A second No. 000 here would give a drop of forty-six volts in all from H to F or a total of ninety-eight to E. This is rather large, but considering the fact that this extreme load at E is only occasional and at known times it is not worth while installing still more copper. Instead, it is a very simple matter to raise the voltage at the station twenty-five volts or so in preparation for the extra load. The feeder should be tied into the trolley at frequent intervals near E and once at F.

Step 7. Now as regards the line from F to C, we reach the final step of reinforcing for the grade F G. The simplest way of doing it is to extend the feeder to *g*, connecting it to the trolley wire at several points. For a load of even 300 amperes at G the drop would be only $46+26=72$ volts, less the overcompounding. On the stretch from G to C help is received from C so that there is little to be feared.

We have now completed the feeding system and may now pause to take account of stock. It aggregates 25,000 ft. of No. 000 wire weighing, in "weatherproof" grade about 15,000 lbs. and costing about $2250. It meets the condition of an average total loss of less than ten per cent in the system at average load and gives not less than 425 volts at the motors under the worst conditions of load.

It should be noted that the feeders are practically determined by the requirements of maximum load. As a general rule, if one takes care of the maximum loads the average loads will take care of themselves.

To facilitate the calculation of feed wire Plate IV shows the wire to be used in transmitting 100 amperes various distances up to 25,000 ft. at 50 volts loss, and for

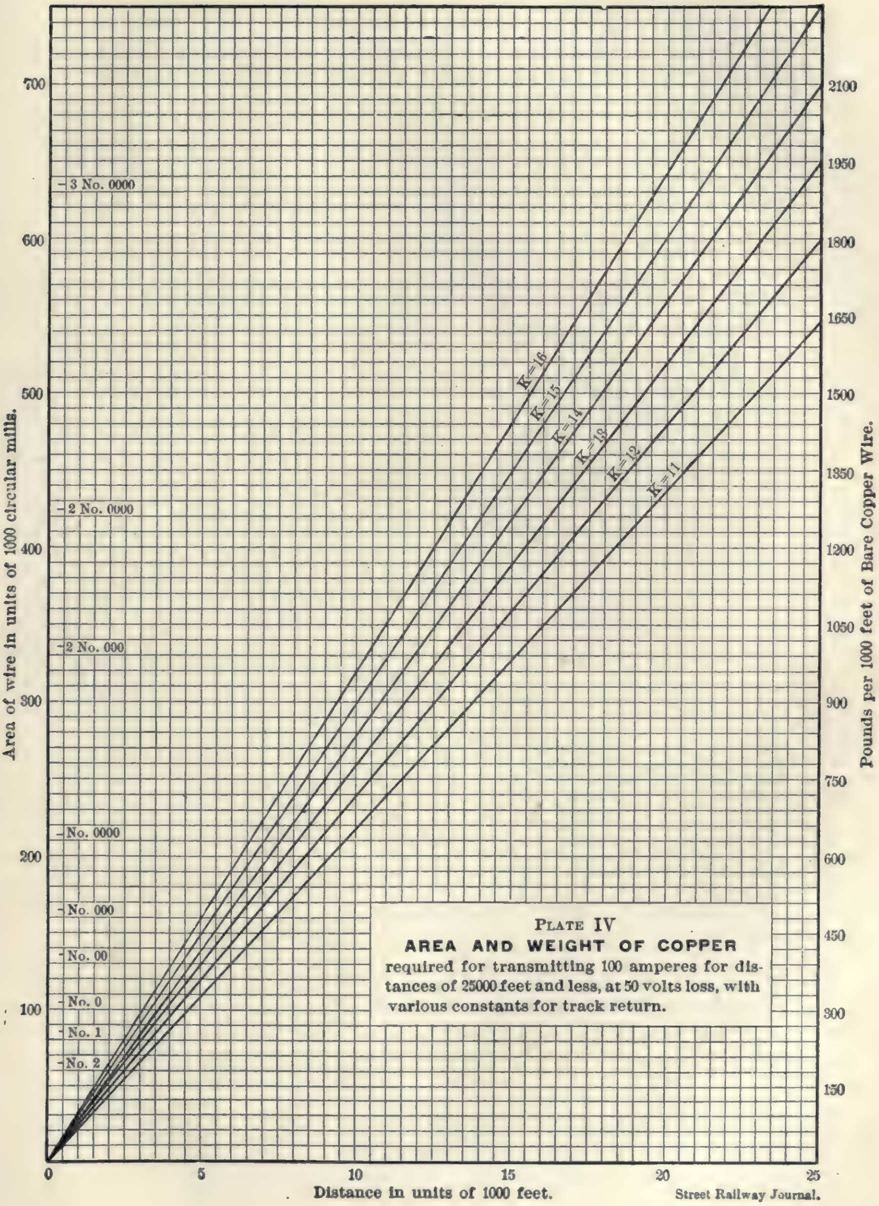


PLATE IV

AREA AND WEIGHT OF COPPER

required for transmitting 100 amperes for distances of 25000 feet and less, at 50 volts loss, with various constants for track return.

Street Railway Journal.

various values of the constant K which allows for the conductivity of the track. The distances herein are lengths of feeder. K=12 is to be used for continuous rails or the most perfect bonding, coupled with moderate service. K=13 applies to roads with very fine track and heavy service or to roads with good track and moderate service, while K=14 should be used for roads having only ordinary track and heavy service or poor track and ordinary traffic. K=14 or 15 may be needed when the track return is unusually poor, while K=11 is introduced for comparison.

It should be noted that the amount of feed wire needed for the case in hand is very different from that indicated in the preliminary discussion. This is evidently due to the face that the actual wire is adjusted with reference to maximum rather than average drop. It is safe in looking into the question of distribution, therefore, to figure the approximate feeder copper for an assumed maximum load varying from twice the assumed average in large and level roads to three or even four times the average in small roads with heavy grades,

As to the actual amount of drop to allow circumstances vary widely. In most cases the conditions of economy are theoretically met by losing five to ten per cent of the total energy in the distribution. This means that the average drop over the whole system, figured on the average current during the hours of operation should be from five to ten per cent. As a matter of fact the average loss is very often determined, just as in the case before us, by the condition that the maximum net drop shall not exceed a certain fixed amount. This condition must always be satisfied and it seldom leads to an excessive average drop. In the case before us the average loss on section 1 is about four per cent, on section 2 about six per cent, on section 3 about three per cent. The average energy loss, therefore, is a trifle over 4½ per cent.

Including 42,000 ft. of trolley wire, weighing about 17,000 lbs, and costing about $2380, the total cost of the copper to give the above loss would be, approximately,

$4630. This cost would have to be doubled to save 2¼ per cent of the total energy. The annual charge for this, counting interest and depreciation at ten per cent, would be $463, nearly $206 for each per cent saved. Now the amount of power, based on the average amperes, is about 2700 k.w. hours per day of eighteen hours; the cost of this per year at two cents per kilowatt hour would be $19,710, of which one per cent is $197.10, showing that it probably will not pay to increase the investment in copper.

The art of feeder design is one that calls for great *finesse* and skilled judgment in assigning the proper values to the somewhat uncertain maximum loads. It cannot be reduced to formulæ that will be of use in anything save special and unusual circumstances. The author has in this chapter, therefore, merely attempted to give the general principles to be followed and some idea of the mental processes by which the final approximation is reached. In another chapter the special case of long interurban lines will be considered.

CHAPTER IV.

SPECIAL METHODS OF DISTRIBUTION.

It is quite obvious that the use of about 500 volts as working potential for railway purposes entails a very serious cost of copper on lines of any considerable length, for in general the cost of copper for a given proportion of energy wasted varies inversely with the square of the voltage.

For instance, to deliver 500 amperes at ten miles distance would require, even with a gross drop of 150 volts, about 2,000,000 c. m. of copper area weighing about three tons per 1000 ft.; in all over 150 tons, costing not far from $45,000, about $225 per kilowatt of energy delivered.

It is, of course, highly desirable to find means for reducing this excessive cost and all sorts of expedients have been tried to that end. The gross loss above assumed is about as great as can be permitted, since on a line with distributed load more loss and greater overcompounding is likely to interfere with the proper performance of the motors and the regularity of the schedule. Very heavy overcompounding increases the cost of the generators and leads to extremes of voltage. In dealing with such a case as that just cited the most frequently advantageous method would be to fall back on some of the regular methods of power transmission which will be described later, but under some circumstances the substation involved in these methods is undesirable, and one must either stand the heavy expenditure for copper or adopt some special means for reducing it.

There are several of these that are in fairly successful use. Of those which require no special devices in connection with the motors the most generally applicable is the so called "booster" system which is essentially a method of raising the voltage on the feeders when the conditions of load demand. Fig. 49 gives a general idea of its character. A B is the line which it is desired to feed, C the main generator connected to the track and ground return at E, and D the boosting generator for raising the voltage on A B.

This booster is a relatively small dynamo connected in series with the main one. Its voltage is proportioned to the extra voltage desired on A B, and its capacity in current is equal to the demands of A B. Its function is to supply the energy which must be lost in the line in order to reduce the cross section of the line copper while preserving the proper voltage and output at B. It is driven by any convenient motive power, generally in practice by an electric motor. In Fig. 49 the booster voltage is taken at 200, while we will assume that 500 amperes are to be delivered as in the case just discussed. The capacity of the booster would then have to be 100 k. w., while that of the main generator might be anything that local conditions on the system should demand. The effect of the boosting system is quite obvious. The initial combined voltage would be 750, of which 300 volts might be lost in the line. The result would then be to reduce the copper needed in the line to one-half of its former amount. The cost of the booster and its equipment including motive power would be $3000 to $4000, so that there would be a net gain of nearly $20,000 in first cost of equipment. Reckoning, as in our previous example, interest and depreciation on this at ten per cent, there is a gross saving of about $2000 per year to offset the cost of the extra power lost in transmis-

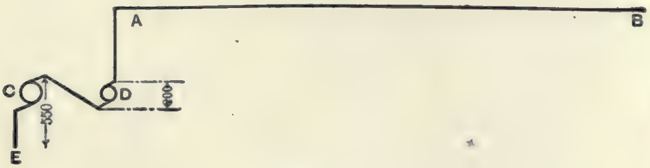


FIG. 49.

sion. This extra loss amounts to seventy-five kilowatts. At two cents per kilowatt hour the cost of the lost energy is $1.50 per hour of continuous service. If the booster were a part of a system demanding the output rather steadily for the full day's run, say eighteen hours, the cost of energy lost would be no less than $9855 per year. This simply means that it seldom or never pays to lose so great a proportion of energy in transmission. It is evident, however, that it will pay to use the booster up to about three hours per day of service at full load. It is, therefore, well suited for helping to tide over the times of unusually heavy traffic. Plate V shows a typical motor boosting set.

We have already seen that these extreme loads really determine the copper necessary for feeders, so that the booster system, if used judiciously, may save a large investment in copper at the cost of an amount of wasted energy that is well within the bounds of economy. The system is therefore much better suited to the operation of long feeders than to the more general use of a station. Such indeed was its original use in incandescent electric lighting at low voltage. It has proved for this purpose very useful indeed, rendering it possible to take up the loss in long feeders at times of heavy load, and to operate lines too long to form a proper part of the main system. It thus has a very useful field in connection with existing plants, but it is distinctly an adjunct, not a proper general method. Line losses which necessitate the continuous waste of more energy than can be compensated by the ordinary compound wound generators are seldom or never justifiable even in a portion of an extended system. If thus partial they are simply less bad than if the whole plant violated the conditions of economy. In its proper sphere the booster accomplishes the same end as the employment of extra voltage in the generators in a case such as was suggested in the last chapter.

As in every other case of heavy drop in the line the boosting system involves certain difficulties in preserving sufficiently uniform voltage along the whole line. When

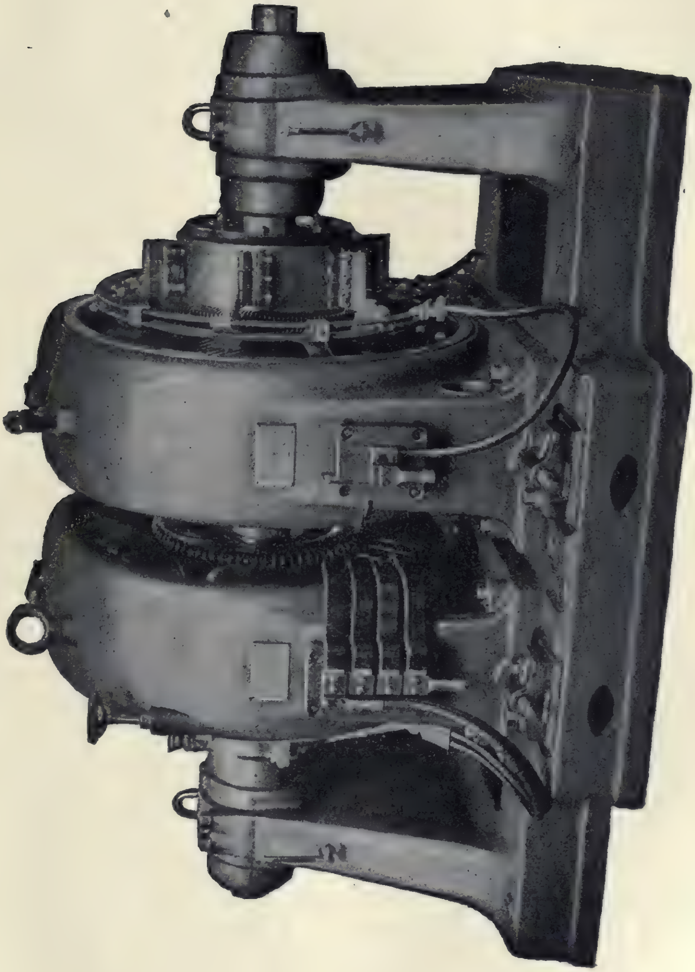


PLATE V.

properly applied for railway purposes it should become the equivalent of an enormous overcompounding applied, not to the whole system, but only to such parts of it as require reinforcement. Take the case of a simple interurban road (Fig. 50). Its office, let us suppose, is to connect cities C and D in addition to handling a considerable local traffic in D and a larger one in C. The power station, at A, was originally devoted to the local work in C and now has to be utilized to operate the whole system. The distance from A to B, the center of distribution in D, is ten miles. Under what circumstances and how may the boosting system be profitably employed? Let the maximum sustained output in D be 500 amperes, including both local traffic and interurban cars. From what has already been said it is clear that if these 500 amperes were needed continuously the booster system would be simply a rat hole into which the management would pour about $8000 per year. On the other hand if the 500 amperes is a maximum load reached normally only a couple of hours a day, boosting could be profitably employed. No system is better fitted for furnishing additional power over moderate distances during brief periods of excessive load. Just how long boosting could be used to advantage would depend on the character of the variations in the load. The general rule regarding the economics of the matter is that a drop in the line great enough to necessitate boosting at average load is never justified, while if at an economical average drop the drop at maximum load is too great to be

FIG. 50.

conveniently overcome by ordinary compounding, boosting is eminently useful.

If the line A B (Fig. 50), when designed for a certain drop at average load, say, five per cent, gives no more than fifteen per cent or so at maximum load ordinary overcompounding will answer admirably. If, however, the maximum load rises to five or six times the average for which the line was designed boosting is by far the simplest way out of the difficulty.

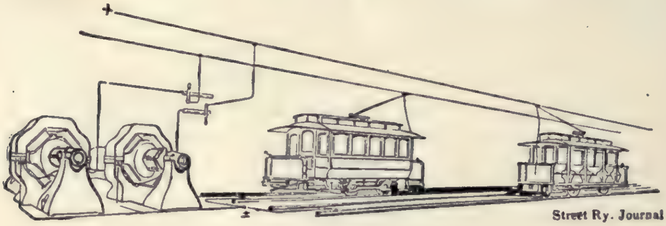
Suppose now A B to be fifteen or twenty miles long and to have a heavy and fast interurban traffic. Could it be worked to advantage by supplying current directly to that part of the line comfortably near the power station and feeding the rest of the line by boosting in sections using boosters of different voltage if necessary? At first thought one might be tempted to say "Yes", for in such case each section would be in full action for but a short part of the day. On the other hand it should be noted that *all* the energy supplied to the distant sections, be it little or much, is supplied under very wasteful conditions, and while such an arrangement would allow a very long line to be served there is generally no excuse in the present state of the art for a device so clumsy and wasteful.

It must not be understood from this that there are no cases in which direct transmission at more than usual line loss is to be preferred to indirect transmission with reconversion. Such certainly exist, but since at the present time it is possible to transmit power at high voltage and reconvert to direct current with a loss not exceeding fifteen to twenty per cent, the field for direct transmission at much greater loss is very limited.

Boosting is preferable to heavy overcompounding when unusually long feeders are exposed to great changes of load, for the reasons already suggested, and it must not be forgotten that when the only loss is that in the line which varies inversely as the load, the all-day efficiency of the system may be fairly high. This matter will be taken up again in connection with the application of the methods of alternating current transmission to cases like that of Fig. 50.

Better than any method of increasing the loss in the line are various methods of increasing the working voltage. These effect the same or greater economy in copper with less loss of energy and are in very many cases preferable to any boosting scheme. Some of them are simply applicable without any changes in the arrangement of the motors, while others require special motors or special arrangements of them.

The application of the Edison three-wire system is the most generally known of these. Its principles are by this time very familiar to the public, consisting virtually of employing two working devices in series as regards the voltage of transmission, while each separate device, connected between one of the transmission wires and the neutral wire, receives only the voltage for which it is designed. The application of this device to railway work is well shown in Fig. 51. The outside terminals of the two generators are connected to two trolley wires while the neutral is connected to the track system. Hence each motor works on about 500 volts, while the transmission of the total energy is at 1000 volts.



Street Ry. Journal

FIG. 51.

In this case the neutral wire is the track, which ordinarily, as we have seen, has a rather good conductivity so that the saving in copper is very material. If the loads on the two sides of the system were perfectly balanced so that there would be no steady flow through the neutral wire, the feeder copper could obviously be reckoned as if we were dealing with a 1000 volt transmission through a complete metallic circuit. For the same percentage loss of energy the copper required will be apparently less than half that needed on the 500 volt system. The case is widely different from that of a lighting circuit since in the latter we are comparing two complete metallic circuits, one of double the voltage of the other, while in the former we are comparing a very good "grounded" circuit with a return circuit of double the voltage. In other words the track, which as a return conductor serves a very important purpose, as a "neutral" is in use only so far as the system is unbalanced and to serve the purpose of a local conductor between cars. To illustrate by a concrete case, suppose a load of 500 k. w is to be operated at a distance of 5000 ft. from the station. For simplicity we will suppose it to consist of a mass of cars bunched on a double track. With the ordinary system we have the state of things shown in Fig. 52.

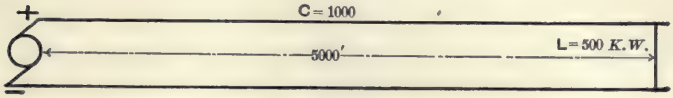


FIG. 52.

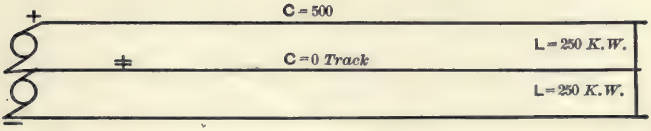


FIG. 53.

Using the constant 13 in our stock formula, the total area of copper comes out 1,300,000 c. m. As a three-wire system in complete balance we have the conditions set forth in Fig. 53.

Here we employ the ordinary formula for metallic circuits and, of course, the constant 11. The copper consequently amounts to 550,000 c. m. in area and since both leads must have this area the total weight of copper necessary is as 11 to 13 compared with the 500 volt arrangement. The enormous conductivity of the neutral, however, renders the matter of balance of comparatively little importance in this case.

The somewhat anomalous character of this result has its origin in the fact that the track, which is or ought to be a first class conductor, is fully utilized in Fig. 52, while in Fig. 53 it can only come to the rescue when the system is unbalanced.

This arrangement of the three-wire system is capable of accomplishing a notable saving of copper only when the track is so poor as a conductor that 14 or 15 has to be used as the constant in the computation concerning Fig. 52. There is, however, another distinct species of three-wire system which is capable of giving greater economy for certain work.

Suppose we make connections as in Fig. 54. Here the outside wires are connected one to an overhead line, the other to the track, while the second overhead line serves as the neutral. The motors may then be connected either on 500 or 1000 volts, an arrangement which would be valuable for interurban work with special motors. This arrangement is not, however, suited for general use, and should be regarded as a mixed system, which, however, is excellently fitted for certain otherwise difficult work. It is closely related to a booster system, the booster not being used in the ordinary way to compensate for line loss, but to give a higher working voltage on lines where it is needed. The two dynamos need not be of the same voltage.

The regular three-wire system of Fig. 53 is capable of saving from fifteen to forty per cent in copper according to the character of the track return. If well balanced it, of course, tends greatly to diminish the electrolytic action on buried conductors and hence is desirable *per se*. The saving in copper, while by no means as great as in the three-wire system for lighting may be sufficient to pay for the difficulty of installation and the expedient has been adopted by several roads. Balancing is accomplished by various means. The simplest is shown in Fig. 55. Here we have a single track road with two lines, A B and C D. The tracks are connected to the neutral lead while the + and — feeders run to the separate branches as shown. This balancing is not very close since it is no easy matter so to divide a branched road that the loads on the two parts shall be equal. Another arrangement less simple, but giving more uniform balance, is shown in Fig. 56. Here the whole track is divided into sections alternately + and —. On double roads either one track is supplied from the + feeder and the other from the —, or each track is subdivided as in Fig. 56, the latter being the preferable method as it preserves the loads on the two sides more uniformly.

FIG. 54.

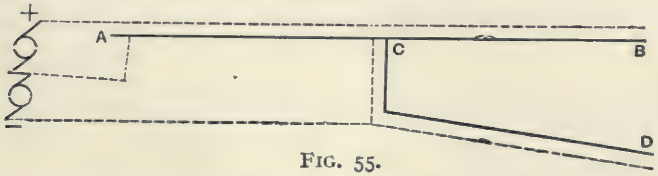


FIG. 55.

A zonal system might be used in large systems, all track within one zone being supplied from the + side, all in the next zone from the — side and so on. In general however the plan of Fig. 56 carried out on all the lines as systematically as the location of the track allows is the best method. The sections may properly vary from a few hundred to several thousand feet in length according to the nature of the car service and local conditions. Very many sections should be avoided as the break pieces in the trolley wire are somewhat annoying.

The three-wire system was tried as far back as 1889 in Milwaukee and has been employed with rather moderate success in Portland, Ore.; Bangor, Me.; St. Louis and elsewhere.

Unhappily while balancing under ordinary conditions is not overtroublesome that wandering of the load which is so grave a factor in electric railway work, has been found to produce serious unbalancing at times so that the three-wire system is at present in rather ill repute.

On the whole the three-wire distribution may be useful, but is not easily managed except in specially favorable cases. The saving in copper entails no sacrifice of efficiency and but little added expense if the station is large enough to make the use of two dynamos instead of one, of little moment. Above a certain size, the price of dynamos increases almost directly as their out-put, so that a pair of machines for three-wire work would then be little if any more expensive than one large one of equal capacity.

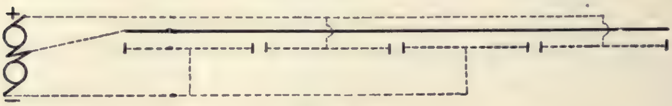


FIG. 56.

A curiously modified three-wire system has been suggested for heavy interurban work, although it has not yet come into use. This is connected like Fig. 53, except that both + and — sides of the system are connected to trolley wires over the same track. Two trolleys are used on each car so that the car is a unit balanced in itself, the two motors taking current from the + and — wires respectively. Fig. 57 shows this arrangement in diagram.

Here A and B are the generators connected respectively to + and — trolley wires, and the track forms the neutral. The motors C and D upon the same car take current from the trolleys E and F and are grounded upon the track neutral in the ordinary way. The neutral only comes into service in the case of need for cutting out one motor, or when one motor slips or develops faults that might cause trouble were the motors simply in series. The track need not be heavily bonded with this construction since it has to carry only occasional and moderate currents. The saving in copper is the same as that already indicated for the regular three-wire system, with the additional advantage that the track connections are easily made and do not require so great and constant care as is the case when a full track return is used.

The employment of two trolleys would be considered a first class nuisance by most electric railway managers, but for heavy work when large currents, say a couple of hundred amperes, are to be dealt with, there is something to be said in favor of trolley contacts in duplicate. These granted, they can be made on two trolley wires without much extra trouble.

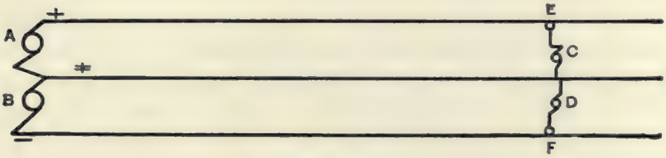


FIG. 57.

This self contained three-wire system appears fairly adapted for heavy interurban service, particularly in conjunction with local service at the termini. As the motors are comparatively independent of ground connections the track could be more easily kept in operative condition through the winter. The system lends itself very readily to cases like Fig. 50, in which the interurban cars could well be connected in the manner described and the local cars in the ordinary fashion of three-wire roads.

None of the methods so far described are able to effect a really satisfactory saving in copper, without involving special arrangements that have proved somewhat serious in practice. Boosters, using the word in its ordinary sense, waste energy in a very objectionable manner, increasing the drop without raising the working voltage at the motors. The ordinary three-wire system involves complication in the general wiring and does not secure nearly as much economy in copper as would be desirable; the system of Fig. 54, while giving considerable economy on the high voltage side requires a special arrangement of motors; and finally the self contained three-wire system, with several excellent properties, demands two trolleys.

What is really wanted for long interurban lines is some way of raising the working pressure on the line, without wasting much energy or introducing troublesome complications. It must be clearly understood that as a matter of economy the higher the voltage the better, providing that voltage can be utilized. If there were no practical objections to employing a 2000 volt trolley system it would certainly be used in preference to juggling with a nominal 500 volt system in the rather vain attempt to cheat Ohm's law out of its due tribute of copper. By far the simplest way of dealing with the long distance lines now frequently found is to face the matter squarely and see what can be done in the line of a higher working pressure on the line and at the motors. It is all very well to work out the most economical methods for supplying 500 volt motors at long distances, but all such are wasteful in the extreme compared with systems working, so far as transmission is concerned, with 1000 volts or more. Boosters and the three-wire system merely make the best of a very bad matter.

In the early days of electric railways even 500 volts was considered rather too high a voltage for motors and dynamos adapted to the severe strains of railway work. A few years of experience have shown that with proper care 500 volt apparatus is entirely reliable and in very many railway systems the working pressure is, save at times of very heavy load, nearer 600 volts than 500. The saving in copper introduced by even a moderate increase in working pressure is very considerable, since, *other things being equal*, the weight of copper required is inversely as the square of the voltage. The following table gives the relative amounts of copper for a few moderate voltages, that necessary at 500 volts initial pressure being taken as 100. The same percentage of drop is assumed in each case.

Volts.	Copper.
500	100.0
550	82.6
600	69.4
650	59.1
700	51.0
750	44.4
800	39.1
850	34.6
900	30.8
950	27.7
1000	25.0

The actual results are slightly better, even, than these figures indicate, since the track return gets relatively better and better as the voltage rises and the current diminishes. To show this we may profitably take a concrete example. Fifty kilowatts is to be transmitted 25,000 ft. for railway purposes. The track is of sixty pound rail, and we will for simplicity assume that the bonding doubles its resistance. The conductivity of the track return is then that of one continuous line of sixty pound rail which equals 1,000,000 c. m. of copper. At 500 volts initial pressure and twenty per cent gross loss, the drop through the track circuit would be 27.5 volts, leaving 72.5 volts drop for the overhead line. This requires about 379,000 c. m. At 1000 volts initial pressure the drop in the track circuit would be but 13.75, leaving 186.25 for the overhead system, which corresponds to nearly 74,000 c. m., a trifle less than twenty per cent of the copper needed for 500 volts, instead of twenty-five per cent as called for by the table.

Obviously this difference depends on the fact that one side of the circuit is a fixed quantity of equal conductivity for all voltages and currents, while this conductivity is a factor entering the computation of the rest of the circuit when different voltages are under consideration.

The economic value of working at higher voltages than customary is thus very evident, even if one may not be prepared for boldly advancing to 1000 volts or more.

So far as apparatus is concerned the difficulty of somewhat higher voltage does not appear to be very serious. With comparatively little modification the type of railway motor now common could be rendered suitable for pressures up to 750 volts certainly. The principal changes would be in the armature winding and the commutator, which would have to be arranged with more segments to bring the voltage per bar within safe limits. With the large and powerful motors likely to be used on long interurban roads the task is by no means formidable, and should not involve any serious increase of cost. As regards the generators the case is similar. On very large units 1000 volts would probably involve difficulties of some moment, since in designing machines for great outputs, 1000 k. w. and the like, it is somewhat troublesome to keep the volts per commutator segment within reasonable limits even for 600 volts. But under ordinary conditions a generator for 750 to 1000 volts is entirely feasible, and for very large capacities the direct coupled units, consisting of one engine and two dynamos, already largely used, are entirely available. Such a combination, shown in Fig. 58, may be very readily operated with the generators coupled in series, giving 1000 volts across the mains, or if convenient, 500 volts on each side of a three-wire system. In some cases, where so much as 1000 volts is not desired, a boosting dynamo may be used with great advantage in connection with a 500 volt generator.

At all events the question of supplying current at a pressure considerably in excess of 500 volts is very simply answered in any of the ways mentioned.

One instinctively asks, too, why ordinary railway motors should not be operated regularly in series for work on long lines, as they are very extensively employed now with series-parallel controllers. There is no good reason why this should not be done, save the danger of excessive and destructive voltage in case of accident to one motor.

Of course, in ordinary series-parallel working, no accident could throw on a single motor more than the 500 volts.

or so for which it is designed, while if both motors were in series on a 1000 volt circuit, a short circuit in one of them, would probably cripple its mate. Even slipping of one might overload the other and imperil both. On the other hand, serious relative slipping, throwing the load on one motor when operating in series, is not common on the dirty city streets where the series connection is most used, and would be still less likely to occur on the comparatively clean and unobstructed tracks of a long line. When one set of wheels slips the other soon follows suit, from the same cause, and there is usually a strong mechanical tendency to equalize slipping. Even admitting the difficulty, there would certainly be no serious trouble of this sort if

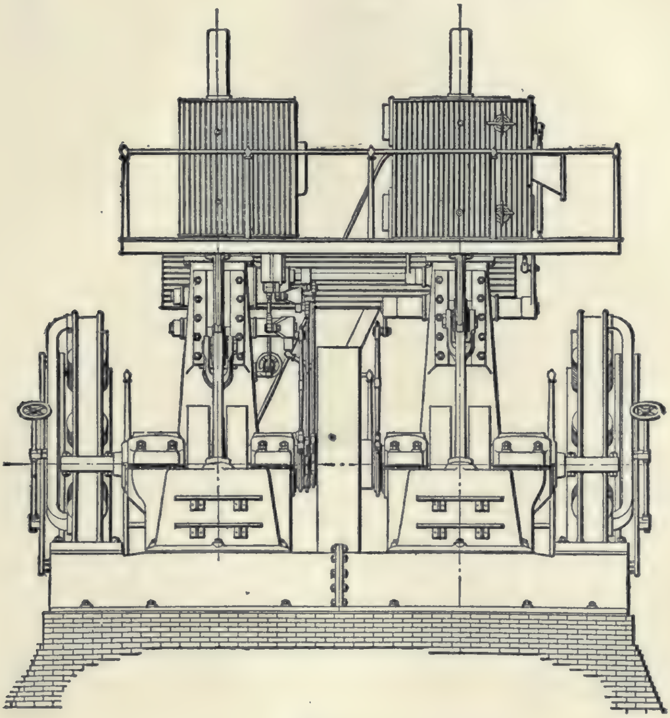


FIG. 58.

both motors were constructed with a larger factor of safety for temporarily enduring high voltage than is now the custom.

There is no momentous difficulty in the way of building a motor to work regularly at 700 to 750 volts, and still less in producing one to stand that pressure for temporary running. And motors which will stand 750 volts at a pinch can safely be operated two in series on 1000 volts with a quite moderate rheostat capacity.

Of course, the question of safety enters into any and all plans for operating at increased voltages.

Of 500 volt continuous currents it can safely be said that they have very rarely caused the death of a human being in normal health. Of shocks to employes there are thousands yearly and the author has yet to hear of a fatal one. The deaths from this cause heralded in the newspapers generally turn out to have been due to other causes. One loudly proclaimed from Maine to California, was due to a gasoline explosion in a car house, another to a collision with an electric railway pole, and so on.

Whether this immunity may be extended to double the usual voltage is decidedly open to question. Currents of 750 to 1000 volts cannot on the other hand be classed as extremely dangerous although quite capable of producing fatal results under favorable conditions. In any case there is no good reason why they should not be freely employed with good construction and proper inspection. In interurban work the tendency is for the road to own its right of way, and in such case any desired voltage ought to be permitted, provided it be installed with due precautions.

To summarize the matter, there is no sufficient reason, electrical, mechanical or ethical, why roads of the interurban class should not be regularly operated at from 700 to 1000 volts, either with special motors or with special arrangements for series running.

A rise from 500 to 750 volts would more than cut the cost of copper in two, while retaining at least the efficiency reached at the lower voltage. At 1000 volts more than three-fourths of the copper would be saved, with the additional advantage of using standard generators instead of those of somewhat abnormal voltage.

It is a fact to be regretted that in spite of the great advantage of even moderate increases in voltage most of the existing interurban roads have hastily gone ahead and equipped themselves with 500 volt apparatus. There is generally some conservative adviser to say, "Well I think copper is a pretty good investment; let us stick to the well tried 500 volt apparatus." True, copper is a very safe investment, so safe that money once locked up in it never gets out again, and 500 volt apparatus is "well tried," but so also is 110 volt apparatus, and for a still longer period. The point of the matter is that most men do not realize that standard apparatus can be made to give good results in more than one way.

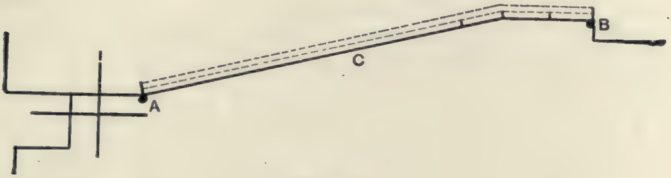


FIG. 59.

A short investigation of the interurban line shown in Fig. 50 will show how terribly uneconomical is the method of operating too often employed, and how the conditions can be greatly improved without involving anything in the least degree truly experimental.

The problem really involved in equipping roads of this sort is as follows: given standard motors and generators as the basis of operations, so to utilize them as to give the greatest economy in construction and operation with the fewest possible variations from every-day practice.

Fig. 59 shows in skeleton form Fig. 50, ready for laying out the interurban part of the system. With the main urban system we need not concern ourselves, since the feeding system would be developed in accordance with principles already laid down. The distance, A B, being ten miles we have already seen that to deliver an assumed maximum of 500 amperes at B would require at 150 volts total drop, about 2,000,000 c. m. of copper, costing about $45,000. This we will assume to be based on a dynamo giving at full load with its overcompounding 550 volts in accordance with ordinary practice. The voltage at the motors will then occasionally drop to 400 volts, certainly the extreme drop that could be tolerated. We have already seen that by boosting to 750 volts and doubling the loss in the line, the copper can be reduced by one-half. At the same time the minimum voltage is raised to about 450, which is much more satisfactory.

Now suppose that instead of doing either of these things we say to ourselves, "These standard motors of ours are intended to operate on 500 to 550 volts like the generators, let us make them do it." In fact these standard railway motors will operate beautifully at 550 volts. Gear them so as to get the full advantage of this voltage and keep down the current. Without any allowance for increased efficiency at the higher voltage the mere change of the running voltage at maximum load from 400 to 550, leaving other things the same, reduces the current to be transmitted for the same energy from 500 amperes to 364 amperes. Now install a boosting dynamo as before, automatically holding the voltage at B at or near 550 volts. Using a 200 volt booster as before, we can allow 200 volts drop, and figuring the copper on this basis it appears that 1,183,000 c. m. will do the work. As a matter of fact there would be an additional gain of nearly ten per cent owing to higher motor efficiency.

The net result is that the copper needed for the work at 500 volts is cut in half while the loss in voltage at full load is twenty-six per cent instead of forty as in the original booster system and the boosting dynamo itself is for seventy-five kilowatts instead of one hundred kilowatts.

As to the actual arrangement of the feeders, for a system likely to involve the use of large motor units and high speeds the author prefers a decidedly heavy trolley wire and would not hesitate in this case to employ No. 000 or No. 0000 trolley wire, putting the remainder of the copper in two cables of about 450,000 c. m. each.

These feeders may be well arranged as shown in the dotted lines of Fig. 59, one of them being carried right on to B the other being tapped into the trolley wire at a few points. The station A is capable of taking care at the increased voltage on a long stretch of the trolley wire without any taps from the feeder, since a No. 0000 wire has high carrying capacity. Transposing one of our stock formulæ

$$L = \frac{c. m. E}{13 C}$$

and assuming one hundred volts drop, a No. 0000 wire can carry one hundred amperes a distance of over three miles unaided. The main precaution that has to be taken is to make sure that when a load at B is forcing the boosting system to its full voltage, a car may not be caught on a dangerously high voltage near the station. Perhaps the simplest way of avoiding this contingency is to cut the trolley wire at some point like C and feed the section next the station direct from the generator without the intervention of the booster. If the conductivity of the trolley wire is needed up to this point for the general transmission it is easy to reinforce the feeders between A and C by an equivalent amount. The exact treatment of such a case must be determined by the relative amounts of true interurban and terminal traffic.

If the problem we have been considering had not involved considerable local work at B, but only interurban work up to that point, it perhaps would have been better to operate the line at 1000 volts, using two motors in series. This procedure would have been feasible if there were, as often happens, an independent railway system at B. It probably would not be often desirable to continue a 1000 volt system through a city for general service, and in the absence of a substation or a local system there is no good way of obtaining the lower voltage desired. The three-wire system may sometimes be used to advantage in doing the terminal work connected with a high voltage interurban line. In conjunction with boosters it may also be occasionally useful in working a long and heavily loaded double track line. Fig. 60 shows this arrangement, which it will be readily seen is really a modified five-wire system. The main generators would then operate directly an ordinary three-wire railway system, while with the assistance of the boosting dynamos they would furnish current for working a heavy suburban or interurban line in the manner just described.

Such are the principal devices for operating extended railway lines from a single power station without any transformation of voltage. They are easy of application and fairly economical, although the voltages dealt with are not really high enough for the purposes to which they are sometimes applied. There is a steady growth of long lines which cannot be economically operated by any of these simpler methods, which at best partake something of the nature of makeshifts. The time comes when a road becomes too long to be successfully worked from a single power station even with the assistance of auxiliary dynamos. A choice has then to be made between operating independent power stations at points along the line, and substations similarly located supplied with power from a single generating plant by the means usual to the long distance transmission of power. The principles involved in these important cases it is now our purpose to discuss.

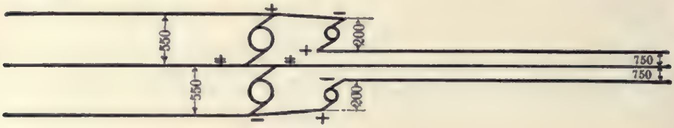


FIG. 60.

CHAPTER V.

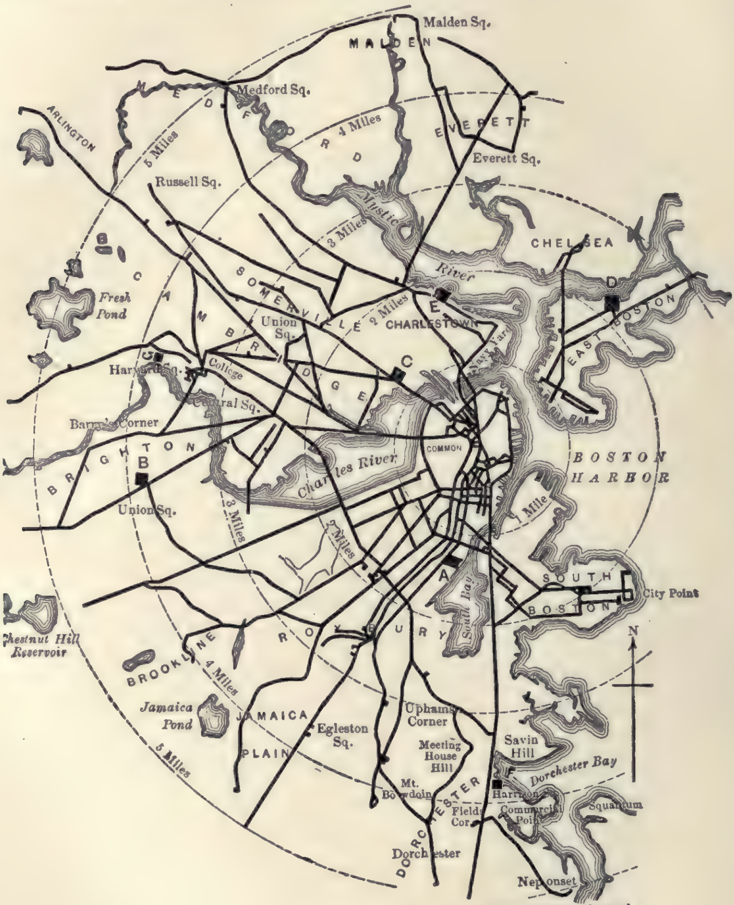
SUBSTATIONS.

From what has already been said it is evident that even with the assistance of boosters, the total amount of copper required for the distribution of power over considerable distances rapidly becomes burdensome. It therefore becomes necessary either to lessen the distance of transmission by multiplying generating stations or to adopt more economical means of transmission than is to be found in the direct supply of continuous current as ordinarily employed. In either case it is necessary to consider the conditions of economy to which the distribution of power from several working centers is subject.

In practice substation working takes one of the three following forms: 1. Auxiliary stations maintained at various points of an extensive network, and designed to reinforce a main station in the supply of distant districts. 2. Distributed stations essentially separate and serving to supply consecutive sections of a line or network. 3. Pure substations effecting local supply of power in connection with transmission from a central station.

Into one or another of these classes fall with more or less exactness all cases of multiple centers of distribution. The first named is found generally in large urban railway systems, which have gradually grown beyond the effective reach of the main generating station. It is the natural and legitimate outcome of extensive growth. The finest example of such practice is to be found upon the tramway system of Boston, Mass. This case is shown in Fig. 61. Here A is the central Albany Street power house of 10,500 k.w. aggregate output. It is reinforced by six auxiliary stations—B the Allston station of 300 k. w., C the

East Cambridge station of 3500 k. w., D the East Boston station of 675 k. w., E the Charlestown station of 1600 k. w., F the Dorchester station of 2000 k. w. and G the Harvard station of 3600 k. w.



Street Railway Journal

FIG. 61.

Still another auxiliary station is soon to be erected. Each of these stations supplies a district which would otherwise be too far from the central station for economical distribution, and they are at the same time so interconnected that in case of accident to one the others can carry on its load with a fair degree of efficiency. This mutual relation is important in that it permits a smaller reserve capacity than would be necessary were the stations independent. For example, the present plant in the Charlestown station consists of two 800 k. w. generators each coupled direct to a compound condensing Corliss engine. It is an ideal plant for the purpose, but as a separate station it would have too few units for safety unless one of the pair should be virtually held as a partial reserve.

The second class is composed in the main of interurban roads too long to be conveniently supplied from a single station. In such cases the use of two or more power stations is the simplest way out of the difficulty, and these stations, having similar functions, are naturally of similar size and character, and so distributed as to supply similar lengths of track as far as practicable. The interurban system centering in Cleveland, O., furnishes a good instance of such practice. This is shown in a sketch map in Fig. 62. It consists substantially of three roads, the Akron, Bedford & Cleveland, the Cleveland & Elyria, and the Cleveland, Painesville & Eastern. The first mentioned is about thirty miles long with two power stations, A and B, of the figure. The former furnishes current for six miles north and nine miles south, the latter nine miles north and five and a half miles south. The two stations are each of 500 k. w. capacity and are substantially duplicates. The second road is seventeen miles long and has also two power stations, C and D. Here C, of about the same size as A and B, sends currents in both directions while D, considerably smaller, handles the section of line nearest the Elyria terminus. The third road is about thirty miles long. It is supplied with power from the Cleveland end, and has also another power station at E. To these must now be added the Cleveland & Lorain Railway, a fine interurban road twenty-seven miles long, having a power station at F supplying the line between Lorain and Rocky River. From Cleveland to Rocky River the cars run over an existing line.

The track is laid with 60 ft. rails and following the suggestions made in this chapter the two 400 k. w. generators are designed for a voltage of 630 at no load and 700 at full load.

Roads of this character can readily be extended by increasing the number of power stations and using boosters. Indeed this was the original method proposed for working long lines and in very many cases may still be the best method, at least until there has been further development in alternating motors for railway service. It is interesting to note however that stations A and B are equipped with com-

FIG. 62.

posite generators fitted to deliver alternating or continuous currents or both, so that one can eventually become merely a substation to transform energy received from the other. At present both stations are worked in the ordinary way.

The third class, true substations, is just coming into existence, as it is a result of the extension of interurban work. It includes all cases of power transmission to distributed stations and at present involves the use of motor generators or their equivalent. Whenever alternating motors for railway service shall be thoroughly worked out, this class of substation work, freed from the present necessity of rotating apparatus, will be likely to lead the others in importance. At present it is being used rather extensively as a substitute for the second class of substation.

The first example of this substation work in connection with power transmission was the Lowell (Mass.) one shown in Fig. 63. The total length of the line is nearly fifteen miles and all the power is supplied from the main power station A, which is equipped with four 100 k. w. composite generators giving either three phase or continuous current. A bank of raising transformers gives a 5500 volt, three phase current on the line. This is transmitted to the two substations B, nine miles from A, at Ayer's Mills, and C, fifteen miles from A at Nashua, N.H. These substations are duplicates. Each contains two 75 k. w. rotary transformers, together with the necessary switchboards and bank of reducing transformers. Station B was started first and supplies the middle section of the line, while the Lowell end forms part of the regular street railway system and is fed from A. C, the Nashua substation, feeds the terminal portion of the line and provides the local service in Nashua, replacing a steam power station. At A, the generators are operated regularly in parallel and in each substation the rotary transformers are run in parallel.

The details of some of these typical substations will be taken up later; for the present purpose it is enough to outline them sufficiently to emphasize the economic conditions on which they depend. These are obviously different in the different classes, but in all we have to deal with the same general circumstances.

The time comes in the growth of a great urban street railway system or the development of long interurban lines, when the cost of transmission of the necessary power becomes very burdensome on account of the long distances.

Street Railway Journal

FIG. 63.

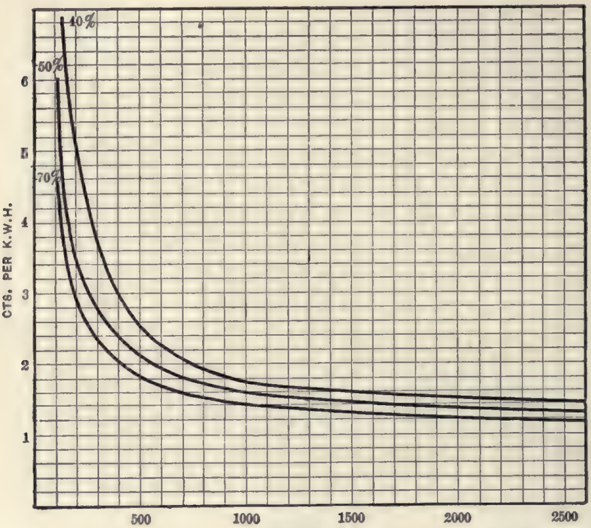
Something has to be done, but to define the particular thing which is best under the circumstances is generally far from an easy task. The operation of substations of any kind means usually an increased cost of power delivered at the station switchboard, incurred in order to save a heavy expense in power distribution.

Minimum total cost of power is the thing to be sought. If generated in a single central station it can be delivered at the switchboard cheaply, but the total cost per kilowatt actually used may be quite high. On the other hand if the power is generated in separate substations the cost of generation is raised and that of distribution lowered. In substations of the third class, the original cost of generation is low, but the transmission of power to, and the maintenance of, the substations has to be balanced against the cost of distribution from the main station direct, and the cost of generating at separate stations.

This balancing of costs involves very nice discriminations and deals with somewhat uncertain factors. The true cost of electric power itself is not easy to estimate, and actual data from existing stations are often rendered valueless by disingenuous bookkeeping. There is a great difference between the cost of power computed from fuel and labor alone, as is often done by those who like to deceive themselves, and the cost with all the items of interest, repairs and depreciation relentlessly footed up. It is not unusual to find the item of depreciation deliberately neglected in computing the cost of power and in other estimates. Street railways have been particularly prone to this sort of financial juggling—it is so convenient to increase the capital account for "improvements" instead of withholding dividends really unearned or shouldering a genuine deficit. Without discussing this question of financial morality, we cannot too forcibly remind the engineer not to deceive himself and the manager that if the present trend of legislation and "labor reform" continues there is likely to come a dreadful day of reckoning in which a sinking fund will be sorely needed.

To determine the conditions of economy that govern the establishment of substations, it is first necessary to know the probable cost of electric power in stations of different sizes and kinds. This is not easy to estimate in general, but can be gotten at with fair accuracy for any given set of conditions as to cost of plant, coal, labor and so forth. In small plants the labor item is disproportionately large and the general efficiency less than in large ones. On the other hand in plants of 1000 k.w. output and over the labor item remains proportionately nearly the same as the plant increases in size, and the efficiency rises very slowly. Much too, depends on the average output of the station compared with its full capacity, i. e., upon the point of output at which the engines and dynamos are worked.

To take a concrete case on which to base our calculations, let us investigate the variation of cost of power with capacity of station, on the following assumptions. Plant of condensing Corliss engines or compound condensing high speed engines, supplied with modern accessories and



Street Ry.Journal

FIG. 64,

furnished with steam by water tube boilers. Dynamos direct belted or direct coupled, of best modern types and supplied with first class station equipment. Plain, substantial, brick power house and stack. Coal $3.00 per long ton delivered in coal bins. Interest and depreciation are grouped together at ten per cent per annum.

Taking into account labor at ordinary rates, and assuming a service of from eighteen to twenty hours per day, one can compute the cost of power with tolerable exactness. The results are shown in Fig. 64. Three curves are given showing the cost per kilowatt hour for average outputs of forty, fifty and seventy per cent of the total nominal working capacity. Ordinary care is supposed to be exercised in keeping unnecessary machines out of service.

These results are higher than those often claimed, but they check quite closely with several independent estimates made by different engineers and also with results obtained from actual practice in modern plants, making the necessary corrections for cost of fuel, etc.

A casual inspection of Fig. 64 shows several important facts very plainly. First, under 500 k. w. capacity the cost of power per kilowatt increases very rapidly as the station decreases in size. For example, following the 70 per cent curve, the cost per kilowatt hour in a station of 500 k. w is 1.8 cts., rising to 2.6 cts in a 250 k. w. station.

Second, above 1000 k. w. output the cost decreases quite slowly with the output, and above 2000 k. w. it would become almost uniform finally reaching a point at which further increase in size would not decrease the cost of power per k. w. h. At what capacity the curves thus become asymptotic is somewhat uncertain, but at present it seems doubtful whether any increase beyond, say, 20,000 k. w. would lead to lessened cost. It is quite certain that several stations now building are beyond the critical capacity.

Hence, generally, when a plant is of such magnitude that sub or auxiliary stations of 1000 k. w. or more can be employed, the cost per kilowatt hour at such stations will vary little from the cost at the main station and most of the saving in feeder copper will be pure gain. On the other hand if substations need but two or three hundred kilowatt capacity they can be operated only at a cost sufficient to balance a large expenditure for copper. To take a concrete case, compare the cost of power from a 500 k.w. station with that from two 250 k. w. substations, as given by the 70 per cent curve assuming the day's run to be 20 hours.

At the 500 k.w. station the cost would be 1.8 cts. per kilowatt hour. At 250 k.w. mean output the total yearly cost of power would be $32,850. Deriving the same yearly output from two 250 k.w. stations the cost would be $47,450, showing a yearly balance of $14,600 in favor of the single station, to offset the smaller cost of feeders and the greater efficiency of distribution possible with the two stations. It is, therefore, easy to get a rough idea of the relative cost of feeding a long line from a single central station and from a pair of stations symmetrically placed. Let A B (Fig. 65) be a line thirty miles in length and requiring a total average output of 250 k.w. with a capacity for 500 k.w. It is cheaper to feed it from a single station, C, at the middle of the line or from a pair of stations, D and E, each centrally located on a half of the main line?

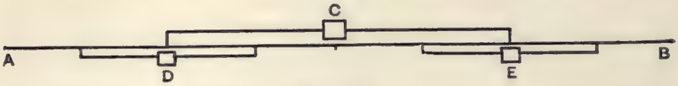


FIG. 65.

We may assume the current in either case to be 500 amperes and the average drop fifty volts. With a single station, taking the average distance of transmission as half the extreme distance in either direction, the length of the transmission would be about 40,000 ft.

Reverting now to our weight formula and writing $3 \times 14 = 42$ as the constant we have

$$W = \frac{42\,C\,L^2\,m}{E}.$$

And applying this formula to our data we find that for feeder copper for the given loss there would be required 336 tons of wire and cable costing in the neighborhood of $94,000. On the other hand if two generating stations at D and E are employed the average distance of transmission would fall to about 20,000 ft., and since the weight of copper required varies directly as the square of the distance, there will be required for the new state of things eighty-four tons of feeder copper costing about $23,500.

The net saving in cost of copper is then $60,500. In laying out the feeders for an actual road these figures would doubtless be somewhat modified by the conditions of traffic, but the general condition is a saving of about $60,000 in first cost as against an extra yearly expenditure of over $14,000 in power. In the average case there would be a strong tendency to use the two stations. There would be just so much less money to raise, the $14,000 would dwindle under the deft fingers of the bookkeeper and growth of the road would soon compel the use of two stations anyway. On the other hand the skillful use of a boosting system might cut the extra expenditure in two and the single plant would be by far the more economical.

The questions regarding probable growth involve very close judgments, and local conditions, such as cost of real estate and nearness to coal and water supply, may often properly turn the scale one way or the other. As between a single 1000 k. w. plant, and two 500 k. w. stations, there would be no doubt as to the propriety of installing the latter, while with a less aggregate than 500 k. w. capacity, the single station would very often be preferable. The longer the line and the greater the aggregate output the greater the advantage of using several generating stations. In most lines of twenty-five or thirty miles in length local or terminal demands for power will indicate the use of a pair of stations by raising the aggregate power or increasing the average distance to which power would have to be transmitted from a single station. Now and then however exactly the sort of conditions set forth in the estimate are encountered and a single station is desirable. In strictly interurban work the suburban traffic near the ends of the line is almost certain to make the substation plan the cheaper. Such is naturally the case in the roads shown on the map (Fig. 62).

On very long lines the question is still further complicated, for the distances may readily be too great to work easily even with two stations, and if the traffic is not unusually great the output of each station may be rather small and intermittent, raising the cost per kilowatt hour by a considerable amount. This amount differs greatly according to the circumstances of load, but we can get a rough indication by making the supposition that the station in question is actually delivering power but half of the time and on the average at half capacity.

Under such circumstances the cost per kilowatt hour will be, in stations up to 500 k. w. capacity, fifteen to twenty per cent in excess of the cost on the basis of a twenty hour run at the same proportional load.

This class of work is that in which the electrical transmission of power at high voltage to the substations is most tempting. The substations on this plan are comparatively cheap and the labor item is small, while the cost of copper for the transmission line is quite trivial. Nevertheless these cases must be very closely scanned, for power transmission from a steam plant in fairly large units, to compete with steam power at cost and economically generated, has still a rather narrow margin for profit.

With this glimpse at the general conditions of economy we may profitably pass to concrete consideration of the three classes of substation working already mentioned.

While the Boston tramway already mentioned is the best example of auxiliary station practice, it is not yet homogeneous, as much of the earlier equipment is still in use and the whole system is the result of both agglomeration and extension. The Charlestown substation is one of the best and latest examples of its kind and will repay a little study in detail. Fig. 66 shows an interior view of this station and Fig. 67, the plan. The power plant consists of two cross compound condensing Allis-Corliss engines, each forty-eight inches stroke, with cylinders twenty-six inches and fifty inches in diameter. Each engine runs at ninety revolutions per minute, is direct coupled to an 800 k. w. G. E. generator and is provided with a steel flywheel built up of rolled plates and weighing a little over forty tons. As the peripheral velocity of these wheels is nearly 6000 ft. per minute, the plate construction is most

FIG. 66.

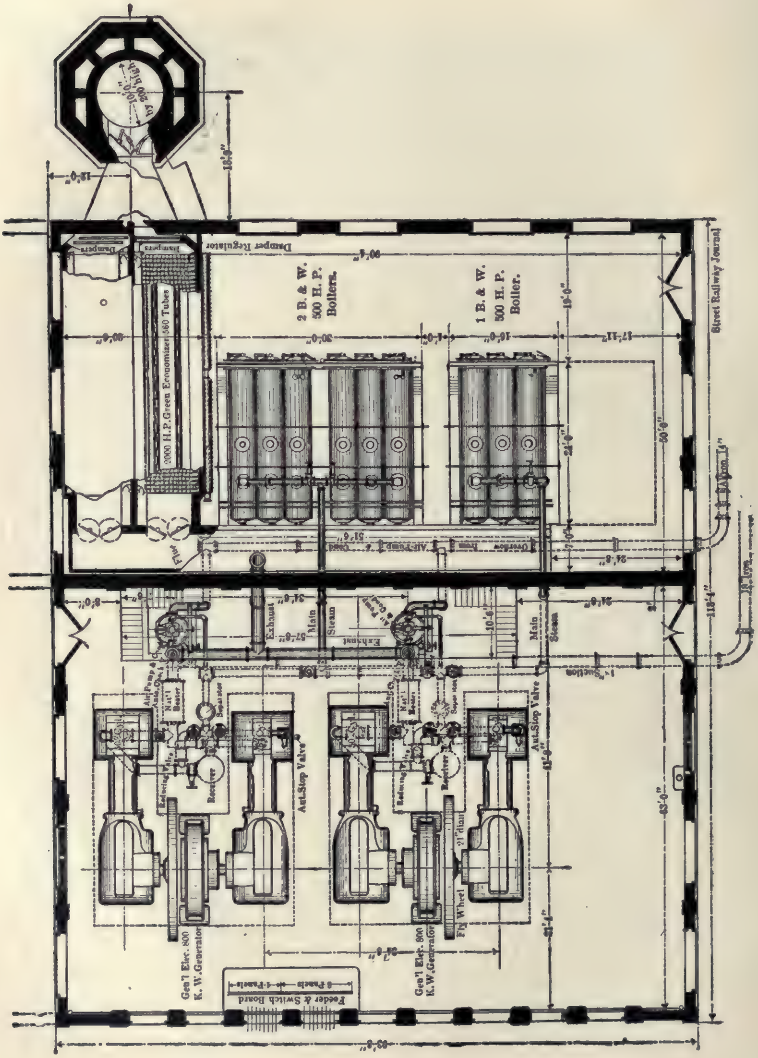

10'0" by 200' high
18'0"
12'0"
Dampers
Dampers
Damper Regulator
90'4"
2 B. & W. 500 H. P. Boilers.
1 B. & W. 500 H. P. Boiler.
19'0"
30'0"
30'0"
10'0"
16'0"
17'11"
2000 H.P. Green Economizer 360 Tubes
24'0"
50'0"
Street Railway Journal
Flue
51'6"
Air Pump
Overflow
24'8"
34'6"
Exhaust
Main Steam
Air Pump & Cond.
Exhaust
Main Steam
Suction
118'4"
Nat'l Heater
Separator
Reducing Valve
Receiver
Aut. Stop Valve
83'0"
Fly Wheel
21' diam
31'4"
34'6"
Gen'l Elec. 800 K. W. Generator
Gen'l Elec. 800 K. W. Generator
Feeder & Switch Board
8 Panels
4 Panels
63'8"

FIG. 67.

important. The choice of compound instead of triple expansion engines was probably a wise one, since while the latter are a trifle more economical at full load, they are less able to cope efficiently with great variations of load, such as met in railway work. Only in the largest stations can they be so worked as to take full advantage of their low steam consumption. The engines are separable, so that in an emergency either the high or low pressure cylinder can be worked as a simple engine.

The boilers are Babcock & Wilcox designed to supply steam at pressures as high as 180 lbs.

The arrangement of the station, as a glance at Fig. 67 will show, is exceptionally good. The whole plant is very compact, the piping between boilers and engines is very short, and, what is rather unusual, the switchboard is where it ought to be, close to the other apparatus, on the same level and perfectly accessible. The accessories are very complete and the whole plant is a fine example of the most advanced modern practice. Almost the only question that could be raised concerning it would be the desirability of using vertical marine type engines, which are of equally high efficiency, slightly higher speed and take up much less floor space. For auxiliary station work with a greater number of power units or for use in a principal station there is much to be said in their favor, but in the case in hand, where ground space is not relatively very valuable, and only two great units were to be installed, honors are pretty even, with this advantage on the side of the horizontal engine that the cylinders can be worked independently with far greater ease than in the case of a vertical engine.

It is altogether probable that power can be generated in this station quite as cheaply as in the main Albany Street station, as the latter is not yet completely remodeled, and the actual result of a year's operation tends to confirm this judgment. In any event a cursory comparison with our curves of cost shows that the output of the Charlestown station is great enough to bring it to a very good point. If properly handled it should produce power at a price not more than one mill per kilowatt hour greater than the best that can be done in the principal station. This difference is so small as to be more than offset by the mere loss in energy that would be incurred in transmitting the power concerned from the main station without involving an overwhelming expenditure for copper. A loss of ten per cent in transmission would wipe out the difference and involve the expenditure of many thousand dollars in copper to boot. A general idea of the economy of this and other auxiliary stations can be had as follows:

Given 1000 k. w. to be delivered an average distance of 10,000 ft. from the principal station for twenty hours per day, and a difference in cost of generation of one mill per kilowatt hour between principal and auxiliary stations. Is it cheaper to run the auxiliary stations or transmit the power?

The amount of power under consideration will cost at the substation $20 per day more than at the principal station—$7300 per year. To offset this we have the interest on the copper necessary for transmission and the loss incurred in the transmission. Allowing five per cent loss in transmission we have a net loss of 1000 k. w. h. per day, costing not less than $10 and in most stations more.

The copper necessary for the feeder line at five per cent loss would be about 168 tons not including the insulation, costing in place not less than $50,000. At ten per cent for interest, depreciation, repairs and miscellaneous charges, the annual charge would be $5000 per year, leaving an annual balance of $1350 in favor of the auxiliary station method.

This advantage would exist *pro rata* for smaller power transmitted so long as the difference of one mill per kilowatt hour might hold. With a difference proportionately so small one may say that auxiliary stations will begin to pay at a radius of from a mile and a half to two miles from the principal station and at greater distances become rapidly more and more profitable.

Unless some one locality shows marked advantage as a point for the cheap production of power, there is little cause for a principal station, for a better distribution can be had from two or more stations of nearly the same output, each taking care of its own portion of the general network. This is evident from two separate considerations. First, the cost of power per kilowatt hour is less, and second, the stations can reinforce each other to better advantage when they are tolerably uniform. If separate stations are to be used at all, the whole district is on the average better served in this way. These matters however usually settle themselves in the process of natural growth without opportunity for theoretical adjustment.

In distributed stations for interurban and long distance work, approximate equality is the rule except as local suburban traffic may call for separate treatment.

The two stations of the Akron, Bedford & Cleveland Railway already mentioned are thoroughly typical of modern practice in this respect. Fig. 68 shows the interior of the Cuyahoga Falls substation of this road. It is specially interesting as being adapted for transformation into a power transmission station, if growth of the road should render such a change desirable at some future time. The generators, as already mentioned, are composite machines, supplied with the ordinary commutator and also with a set of outboard collecting rings to deliver from the armature winding polyphase currents which would otherwise be commutated in the ordinary way and sent out upon the line as continuous current. Each machine is of 250 k. w. capacity and delivers either continuous current at 500 volts or alternating currents at 380 volts and 3800 alternations per minute. Within reasonable limits both kinds of current can be delivered at once. Although at present the only use of the alternating current is for a comparatively trivial amount of lighting, by installing a transmission line with raising and reducing transformers it becomes an easy matter to exchange power between the two stations, in case of accident to either of the steam plants or to trans-

FIG. 68.

mit all the power to the Bedford station, in case the Cuyahoga Falls plant should be operated by water power. And in case it should prove desirable these same convenient generators could supply polyphase current to the trolley line through the medium of static transformers. The polyphase motor has much to commend it for railway service as we shall see later, and to be prepared is to be on the safe side.

As regards the general design of the station in question, it is good. The Westinghouse composite generators lose no efficiency by the addition of collecting rings, and direct belting to a Corliss engine is, with the exception of direct coupling, as efficient a method of operation as could be desired. And direct coupling to composite generators involves great practical difficulties at ordinary frequencies, as will be explained in the discussion of alternating appatus and methods.

As to the economy of the arrangement of stations adopted in the case of this road, it is quite safe to say that the distances involved and the terminal conditions demand the use of two stations rather than one, and each station is sufficiently large to ensure tolerably economical production of power.

Of the possibility of using one station as the generating point and transmitting power to the other we will speak later in discussing special substations.

Roads like the Akron, Bedford & Cleveland, however, can very frequently be best operated without recourse to special methods of power transmission, particularly if the working voltage is carried somewhat above 500 volts, as it should be. It should be noted that as regards the best type of substation working these interurban roads stand in a position quite different from that occupied by the extension of similar methods to long distance traffic at high speeds, such as has often been suggested and will probably be tried ere long. The interurban road has relatively more trains and more stopping places, thus producing a more uniform call for power than would be found in an electric express service. Hence each substation would have a better load factor and more continuous service, rendering it more easy economically to run separate generating stations. When the service in any part of a road is decidedly discontinuous and gives a poor load factor, that substation will give the best economy which has the lowest fixed charges for interest, depreciation and labor. Hence in this class of work power transmission with true substations, is likely to give better results than independent generating stations. Coming now again to this class of true substation, the only well developed example is found in the pioneer power transmission plant of the Lowell & Suburban Electric Railway running from Lowell, Mass., to Nashua a distance of nearly fifteen miles. Fig. 63 shows a sketch map of the route. The first step was the transmission of power from the Lowell generating station, A, a little over nine miles to B, the substation at Ayer's Mills. A little later the generating station which had for some time done service at Nashua was shut down and replaced by a substation, C, fed from the transmission line from Lowell. The need of this terminal substation was largely due to the local traffic in Nashua which is a place of some 20,000 inhabitants; and a heavy summer suburban traffic extending from Lowell to a pretty lake and picnic ground five miles north called for ample power in the initial section of the road. Hence power was transmitted direct to Nashua for the load there and also to an intermediate point which could supply the line in the intermediate section and help out the suburban loads at each terminus.

The generating station in Lowell is common to the local service of the railway line and to the transmission apparatus proper, which was added when the long distance line was undertaken.

The generating apparatus for the transmission plant consists of four 100 k.w. composite generators delivering either direct current at 500 to 550 volts or three phase current at about 320 volts. In this case the three phase side only is in regular use, and the current is transformed in a bank of substation raising transformers to a pressure of about 5500 volts, at which it is transmitted to Ayer's Mills and to Nashua. The frequency of the three phase current is about thirty complete cycles per second—3600 alternations per minute.

The four generators are habitually operated in parallel as is the case with many of the recent polyphase stations, and the whole plant from end to end is substantially in parallel. The use of composite generators in this case seems to be somewhat unnecessary, as there is little reason to suppose that they will ever be diverted from their present function to supply an extra demand for continuous current. The generators, too, are belted to a common shaft instead of being direct belted or coupled. Altogether the generating plant could have been decidedly improved by more specialization. On the other hand the substations are well planned. That at Ayer's Mills is a compact frame building divided into two rooms. One of these contains the bank of reducing transformers and the

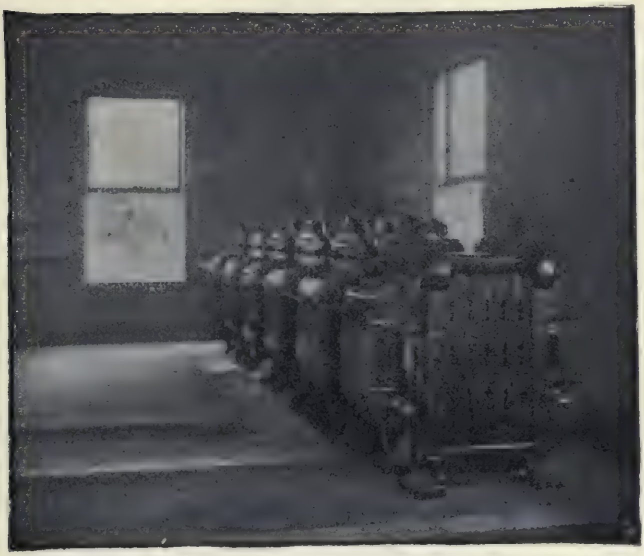


FIG. 69.

high tension switches and accessory apparatus, including a little direct current motor for furnishing the air blast which is used to facilitate dissipation of heat from the transformers. Fig. 69 shows the interior of this transformer room. The other room is devoted to the two seventy-five kilowatt rotary converters that form the power equipment, together with the low tension three phase switchboard and the railway switchboards for the continuous current side of the machines. This pair of rotary converters is well shown in Fig. 70. These machines have proved to be singularly convenient, being highly efficient, capable of enduring severe overloads without difficulty, and generally quite unexceptionable in their performance.

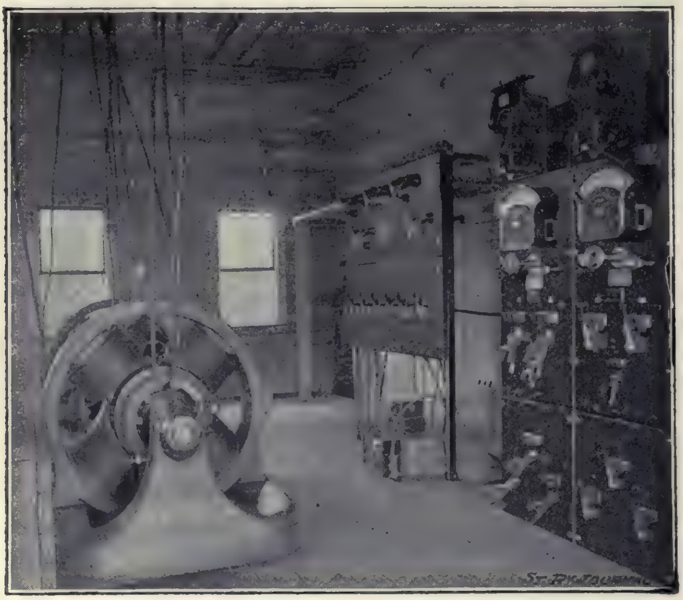


FIG. 70.

The Nashua substation, C, was, so far as apparatus is concerned, practically a duplicate of that at Ayer's Mills.

This Lowell-Nashua line is hardly long enough to give power transmission its full measure of economy. If this line were to be considered by itself it would be an open question whether the work could not have been done quite as economically by a carefully planned booster system, retaining the Nashua generating station. In case of considerable extension either beyond Nashua or in some other direction, the transmission plant will rise to its full importance.

As regards the economy of substations so constituted the case is somewhat as follows: without the transmission the items to be considered would be the loss of energy and the cost of distributing the power generated in the ordinary way at one or more stations. On the other hand would be the cost of the transmission line and apparatus, the energy lost therein, and the cost of building, maintaining and operating the substations themselves. Substations with rotary converters or equivalent apparatus do not, it is true, require a large amount of labor in their operation. But they do require the constant attention of one or more dynamo tenders, and the same general care that would have to be given to the electrical part of a generating station of similar capacity. In this connection it is interesting to note that the rotary transformers at Nashua have recently been moved to Ayer's Mills, and the line is now operated with a single substation. The use of storage battery substations has recently become rather common and among others a typical example has been installed in connection with one of the suburban lines forming a part of the Philadelphia, Pa., electric railway system.

This particular station however, serves in the main merely as a voltage regulator, and is in so far a makeshift that no general results of value can be derived from the somewhat favorable results there obtained.

As a local source of energy transmitted from a central station the storage battery is rather inefficient, high in first cost, and subject to considerable depreciation. Its chief merit is its steadying effect on the load of the central station. The efficiency of the battery in point of energy under favorable conditions may be taken as high as 80 per cent, at least 10 per cent less than the efficiency of a rotary transformer, while it costs nearly twice as much per kilowatt of capacity and has certainly a higher rate of depreciation.

Furthermore it requires about the same amount of attention. Whether any probable improvement in the load factor of the main generating station can overbalance these disadvantages, save in small stations, is very doubtful.

In modern electric railway practice the load is far more uniform than is generally supposed and the conditions of economy are better. For example in the Dorchester substation of the Boston tramways the average daily load ranges from 70 to 75 per cent of the full load of 2000 k. w. and the total consumption of water per k. w. h. is 18 to 20 lbs. This result, for compound condensing engines, leaves but a small margin for improvement by the use of any device for steadying the load.

It is quite safe to say that, in a large system, battery substations, large or small, are less economical than substations with rotary converters.

In the Philadelphia case just mentioned the battery substation, with a maximum permissible output of 500 amperes, cost including the building, $25,000. This is about twice the cost of a rotary converter station for the same output, requiring no more attention and having a lower rate of depreciation than the battery.

In charging the battery a booster has to be used at the power house, and it is a question whether a properly designed booster system without the battery would not have served the same purpose quite as well at a much lower cost.

It is however probable that on an extensive system with a moderate and wandering load, storage battery stations charged at high voltage, may, in virtue of steadying the load prove more serviceable than rotary converter stations. Their use, however, is certainly of special, not of general, applicability and while sometimes convenient as a makeshift or as the simplest solution of a special problem, they should be employed very cautiously in the present state of our experience. It is now not uncommon to use batteries purely for the purpose of steadying the load and thus improving the load factor, and while few such plants have been in operation long enough and under exact enough conditions to determine accurately the net results, the practice is worthy of more than a passing mention. The logic of the process is to connect a battery in parallel with the generator, charging at times of low load and discharging at times of high load. The beneficial result is two-fold; the generator is enabled to work at a nearly uniform load well up toward its full capacity, and hence at high economy; and by this reduction in load fluctuations it becomes possible to use a smaller generating outfit than would otherwise be the case. The price paid for these advantages is the use of the battery, high in first cost, having a rather stiff depreciation, and not of high efficiency.

To form a clear idea of the conditions which exist we may refer to Fig. 71 which is taken from a plant in regular operation and shows the total output, battery output and generator output, for a brief typical period. In the first place it should be noted that the battery does actually take care of most of the fluctuations, reducing the generator load to a fairly steady quantity. An inspection of the generator curves shows that a 50 k. w. machine could have done the work perfectly well and that it would have worked at a load factor of nearly 90 per cent. Unaided by the battery a machine of nearly 100 k. w. would have been required, working at little better than 50 per cent load factor. Still greater fluctuations might be reasonably expected, but it is probably not far from the truth to say that by combining generator and battery in a case like this the generator need not have a capacity of over 60 per cent the normal plant capacity. The plant with generator alone would work on the average at rather less than half its rated capacity while the plant with battery would work its generator at nearly

80 per cent load and the battery would stand the rest. The battery would then be normally perhaps 40 per cent of the plant with a power of doubling its discharge rate when necessary. Now let us see to what this leads. Roughly the cost of the two plants would be about the same, for the cost of battery would more than offset the extra capacity of generator boiler and engine required to displace it. The general effect is to raise the load factor fully 30 per cent. The effect of this on the economy of the system is great, as appears from Fig. 64. It is extremely difficult to predicate the cost of power in such small units, but it is perfectly safe to say that the smaller plant being worked at higher efficiency would produce 1 k. w. h. at not over two-thirds the cost in the larger plant. Of course it has to produce more power since each k. w. delivered through the battery means at least 1.25 k. w. delivered to the battery, and probably rather more if the battery takes most of the fluctuations. Let us assume that the smaller generating

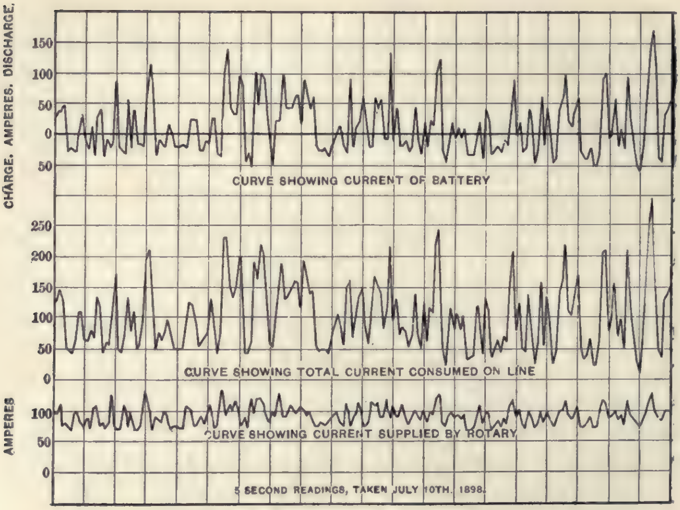


FIG. 71.

plant can deliver energy at 4 cts. per k. w. h., and the larger one at 6 cts. per k. w. h., the total energy required being 500 k. w. h. per day on the line. From the larger generating plant the cost of power would be $30 per day. The battery plant would furnish, say, 250 k. w. h. direct, costing $10 and 250 through the battery. Allowing this a net efficiency of 75 per cent, it would require 333 k. w. h. which at 4 cts. amounts to $13.32. Hence the battery plant would save in the gross cost $6.68 per day or annually 10 per cent on nearly $25,000—evidently a handsome saving. Where so great a change can be made in the load factor of a small plant, a battery is well worth using in spite of extra cost and care. As the plant increases in size a point is reached at which the cost of and loss of efficiency in the battery, offsets the saving from improved load factor. Just where this point is, is hard to say, but if the load factor of a plant is 40 per cent or less, the battery question is worth raising and investigating carefully. In case a considerable saving is probable one may be justified in putting the battery at some distance from the generating plant thus getting the advantage of a substation to offset the extra attendance and loss in charging, and if the load is light and badly scattered, the logical outgrowth of the situation may be several battery substations. The essence of the matter is the possible improvement in load factor.

The whole matter can perhaps best be discussed by taking up a concrete case and treating it first by the ordinary methods of distribution, and second, by a transmission system.

We will assume an interurban line twenty miles long, A B, Fig. 70. The suburban sections, A C and B E, each requires an actual average output of 200 k.w. which may practically all be concentrated in A and B on occasion. The interurban portions, C D and D E, require together an average of 100 k.w. nearly uniformly distributed. What is the best arrangement for supplying power; stations at A and B, stations at C and E, a single station at D or transmission of all the power from some one point with substations at one or more of the others?

Of the plans with two generating stations, that with stations at A and B is undoubtedly the better since the terminal loads are so considerable. The single station at D requires a little consideration, because the difference in cost of power between a 500 k.w. station and two 250 k.w. stations is very material. Of the possible transmission plants, that comprising a generating plant at one end of the line and a substation at or near the other is at first glance the most promising. For the total amount of power to be transmitted is very moderate and the subdivision of even this by using two or more substations would only involve useless expense.

We may now compare more closely the plan calling for stations at A and B with that for the installation of a single plant at the point D. On the one hand we have the economy of the larger station—on the other the cost of distributing 200 k.w. at a point ten miles from home.

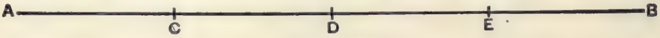


FIG. 72.

Assuming the yearly differences in cost of power between a 500 k. w. station and two 250 k. w. stations to be about $0.4 per kilowatt hour in favor of the former, the yearly difference is $14,600. Now for the approximate cost of feeder copper. If a simple station at D be used we must practically allow for 400 k. w. delivered at a distance of ten miles. Using the formula employed in the previous cases

$$W = \frac{42\ C\ L^2 m}{E}$$

and assuming ten per cent drop we have a call for 940 tons of feeder copper costing about $263,000. Even at twenty per cent loss the feeder copper would amount to more than $130,000, exclusive of the nearer distribution. This settles the matter off hand, for with two stations the average distance of transmission would be hardly more than three to four miles, and the total amount of feeder copper relatively very small. In a less extreme case a closer calculation of feed copper would be required, and the matter could be examined with any necessary degree of precision.

With two generating stations we may as a first approximation assume that on the whole 400 k. w. is transmitted an average distance of 2½ miles, say, 14,000 ft., and 100 k.w., a distance of, say, 40,000 ft. For the first item there would be necessary about sixty-six tons of copper and for the second about 134 tons, in all about 200 tons, costing, say, $56,000.

Now if the power is transmitted from A to B we shall have a saving as before of $14,600 in the gross cost of generating power, but lose about ten per cent in final efficiency since the net efficiency of line and apparatus will be roughly eighty per cent as against ninety per cent for the loss in feeders as above. For a 10,000 volt transmission about twenty tons of copper will be required costing, say, $5600. The transformers and rotary converters with the requisite accessory apparatus may be lumped together at about $50 per kilowatt capacity. Allowing 400 k.w. capacity at the substation the cost of transmission line and apparatus would be between $25,000 and $30,000. Assuming the latter and charging off ten per cent for interest and depreciation we have a fixed charge of $3000 against the plant. Allowing four men at $75 a month each at the substation and five per cent extra on the plant for maintenance of line and repairs we have a total charge against the transmission of $3000 + $3600 + $1500 + 10 per cent of the yearly energy which at 1.3 cts. per kilowatt hour would cost about $4745, in all about $12,845, showing a small saving in favor of the transmission of power. The difference, however, is so small that it could easily be thrown on the other side of the balance sheet by a slight change in local conditions, or on the other hand it might chance to be increased. The exact state of the case would have to be determined by a thorough examination of the change of cost of power with size of station in the localities in question. It goes without saying that the curves given in Fig. 64, while closely figured for the assumed conditions are subject to too much variation to be safely applicable to the decision of a close case. For preliminary investigation however they will be found convenient.

At shorter distances than that just assumed the same apparatus would generally be required and the cost of line would gradually decrease, but so slowly that the economics of the case would remain nearly the same. The minimum cost for the case considered would probably be given by a main generating station at some convenient point between A and C, and a substation about midway between E and B. So long as substation apparatus requires the same attention as generating apparatus, the usefulness of power transmission is limited to a comparatively small field. If, however, alternating current motors come into regular use so that the only substations required shall be static transformers distributed along the line, the use of more than one generating station, save in roads on a large scale, will be needless and wasteful. A very important problem which has of late assumed great importance is the distribution of power by high voltage currents not to scattered stations along a line, but from a huge central power station to its auxiliaries. It is power transmission *versus* auxiliary stations with prime movers—a question deserving close consideration by itself. For example, is it cheaper to generate power separately in such a case as is shown in Fig. 61, or to generate, say at A, and transmit to the other stations? In the matter as thus stated, the general network for distribution is exactly the same in each case and the economic dilemma is an immense central station plus transmission substations *versus* auxiliary stations. For simplicity let us assume as the units to be compared a 15,000 k. w. station with five 2500 k. w. substations with rotary converters, and six separate 2500 k. w. stations.

The fundamental problem is the relative cost of power in a 15,000 and a 2500 k. w. station, each being equipped in the best modern style, and the costs in each case being carried out to the bitter end, including the interest charges due to first cost, so as to put the final charge per kilowatt hour on an absolutely even basis. No practical data on a 15,000 k. w. station are available, but Dr. C. E. Emery has made a most thorough and keen analysis of the final cost of steam power in a 20,000 B. H. P. station. For simplicity we will assume the load factor of 63.8 per cent which is taken in his estimate, since as a matter of practice this figure is quite nearly that regularly reached on the Boston and Brooklyn systems, having similar or greater output.

On the basis of a maximum output of 20,000 h. p. every day in the year, at the above mean load factor, and running twenty-four hours per day, the cost per brake horse power hour is estimated by Dr. Emery to be, coal being $2.24 per long ton,

0.378 cent

Taking this figure for the B. H. P. at the dynamo shaft it is not difficult to make the necessary corrections for the cost and labor connected with the electrical part of the plant and to reduce the result to cost per kilowatt hour. At present prices for material and labor the net result would be

0.62 cent per k. w. h.

This figure is notably higher than some of the published costs of power in existing railway plants of much less size, but such costs generally do not take account of interest and depreciation, which makes a very material difference. Data from existing stations of 2000-3000 k. w. capacity do show, however, that power can be produced in them at from, say, 0.75 to 0.80 cent per k. w. h., with all expenses included. In the present state of knowledge on the subject one may fairly say that in passing from a capacity of 2500 k. w. to 15,000 k. w. it would be imprudent to reckon upon a saving exceeding 20 per cent. Appearances indicate a saving even less than this, if we may judge from the saving over still smaller units.

Now bearing in mind that these costs have already taken into account the difference in cost of erection between one very large plant and six large ones, together with all similar factors, we can take up the merits of transmission at high voltage to rotary converter stations. To take the most favorable case we will assume that the central station furnishes 2500 k. w. directly to the lines and is equipped with high voltage generators, 5000 or 6000 volts, for the remaining 12,500 k.w. To obtain the net cost of power we must take account of five rotary converter stations with reducing transformers, necessary labor, transmission lines, and also the necessary losses in transmission.

Fortunately rotaries are capable of being compactly stowed so that the real estate charges are not exorbitant and while they cannot go without attention, require little extra labor. At high voltage the loss in the lines is not large, and both transformers and rotaries are efficient. We will assume the net all day efficiency of the combination of line transformers and rotaries to be about 85 per cent, which is as high as the facts will warrant, and an average distance of transmission of 15,000 feet. We will also assume that including all apparatus, building, and land, each station of the five costs $90,000 and that only one attendant is on duty at a time in each station. On this basis after making the necessary corrections, the cost per k. w. h. delivered from the rotaries becomes

0.83 cent

and the total net cost of power on the system becomes almost exactly

0.8 cent.

It therefore appears that under the conditions assumed the chances are against any economy of operation, for the assumed saving of 20 per cent in the original cost per k. w. h. in the central station. In the writer's opinion 15 per cent would be a liberal estimate, and this means that the system of power distributed to rotaries would cost nearly 10 per cent more per k. w. h. than if generated in individual stations. In the absence of data on very large stations all these figures have an element of uncertainty; but it is well within the truth to put the case as follows: If there be any gain in the distribution of power by rotary converters on the scale just indicated, it must be sought elsewhere than in the economy secured by concentration of steam plant.

Conditions may easily arise, however, such as will make such a distribution desirable. In the first place there may be one particularly site for a power station by utilizing which enough would be gained to more than offset the losses incurred in transmission. In Dr. Emery's investigation of the cost of power in a 20,000 h. p. station the total cost is subdivided as follows:

Coal	37.3	per cent.
Labor	11.3	" "
Supplies and repairs	17.4	" "
Interest, taxes, renewals, etc.	34.0	" "

Assuming this for the steam power delivered to the dynamos and making the necessary modifications for the presence of the electrical plant, the distribution of the total cost in the latter case will be about as follows:

Coal	32	per cent.
Labor	13	" "
Supplies and repairs	18	" "
Interest, taxes, renewals, etc.	37	" "

These proportions will vary from place to place but are not far enough from the mark to lose their usefulness for the purpose to which we are about to apply them.

A change in cost of coal due to difference of transportation facilities would have to amount to something like 15 per cent of the price to give a reasonable chance of offsetting the extra transmission costs. Labor, and supplies and repairs, evidently will not vary appreciably except for the cost of water, while of the rest only the costs of real estate and foundations give a chance for material variations. Concurrent advantages with respect to coal, water, real estate and foundations in favor of a particular site may render transmission to rotary converter stations decidedly desirable, but it is to these factors, rather than to general considerations, that we must look in drawing our conclusions. Save in rare instances no single item mentioned is likely to turn the scale.

Two further factors must be taken account of; first the absolute magnitude of the plant, and second the number of substations involved. As to the former consideration, doubling the assumed output with the same number of substations as before would leave so small gain in economy by concentration as to require an extraordinary combination of favorable conditions to give even a prospect of final economy.

At half the total output first assumed, on the other hand, the costs of power generated in one station and transmitted to five others, and of power generated in six stations would be so nearly equal that any considerable advantage in favor of one site for a station would settle the matter.

In the case of employing only two or three stations, the chance for economical transmission is usually very small in urban work—the interurban situation has already been discussed.

If, however, advantage can be taken of transmission to rotary converters to considerably increase the number of substations, the conditions are radically altered. As has already been shown, increasing the number of stations decreases the feeder copper enormously, and in the author's judgment the logical way to work transmission to rotary converters is to carry the number of substations beyond what would be desirable if substations with prime movers were to be installed. In this way a very considerable advantage can be gained if conditions are favorable. The adverse factors are first, the additional labor required; second, the absolute density of the traffic, determining the normal output in any given part of the system; and third, the effect of wandering of the load on the maximum output in any district. As regards the first count it may be well to note that wages of one constant attendant will amount to 10 per cent on the cost of about fifty tons of feeder copper, hence there is an evident limit to the profitable use of apparatus requiring attendance. In the next place, the actual output regularly demanded in any one section predetermines to a considerable extent the output which must be available nearby, and finally the wandering load demands heavy output at particular points at particular times, possibly half the total load being concentrated in one small region toward 6 P. M. Hence one must sometimes deal with large units whether other conditions are favorable or not.

In large urban systems the whole problem gets tremendously intricate and cannot be settled on general principles. Enough has been said to indicate the line of reasoning to be followed and the rest must depend upon local conditions as they may exist. But the questions to be decided are, as has been shown, so close that the final solution of the matter—and the best solution—is likely to be different in different places. In most instances a close study of the details should lead to the use of more than one generating station, re-enforced by substations with rotaries where they can be advantageously used. And one such substation ought be pretty near the centre of the load produced by the maximum concentration of cars. The transmission method is a very valuable one when properly applied, but it has economic limitations that should be kept steadily in mind.

Just at present the most promising method of operating roads of moderate length seems to be the use of direct feeding at high voltage, by boosting, the three-wire system or the like. When the length reaches fifteen or twenty miles, the choice is between separate generating plants and true substations with the advantage of the latter slowly increasing with the distances involved. In cases where the amount of power involved is very great, as in large urban plants like the Boston one or in extensive suburban service such as is likely to be met in the transformation of steam into electric service, auxiliary stations are most likely to give the minimum cost of power, since the size of each plant can be so considerable that further increase will decrease the cost of power only to a minute degree. The greatest future gain in systems of moderate size is to be sought in the possible use of alternating motors.

CHAPTER VI.

TRANSMISSION OF POWER FOR SUBSTATIONS.

The transmission of power for railway purposes is a comparatively simple matter so far as methods are concerned. Inasmuch as railway dynamos are already worked at a comparatively high voltage, as high, in fact, as any continuous current generators of large output, there is little reason to consider continuous current methods for transmitting power. Large generators of this class cannot be built for voltage high enough above that already used in railway practice to make it worth while to transmit current for transformation by motor generators. Thus it is that for the purpose in hand one need only be concerned with the use of alternating currents, polyphase and other, and the transmission of power at high voltages, from 2000 volts up to 10,000 volts or more.

To begin at the beginning, it should be understood that all generators from their constructional features are essentially fitted for the production of alternating currents. When continuous current is desired the current derived from the armature windings has to be commutated to reduce it from its original alternating form to being unidirectional. Take, for example, a simple drum winding intended for continuous current, such as is shown in Fig. 72. Tracing out the direction of the currents as shown by the arrows one sees immediately that the two halves of the armature are in parallel between brush and brush. When the armature has turned through 180 degs. the coils that originally were under the + brush have come under the — brush and are generating E. M. F. in a direction opposite to the original one. All coils as they pass under a given brush are delivering current in the same direction, but when they have turned 180 degs. the current direction in them is reversed and they are properly related to the other brush.

If, now, the brushes turned with the armature they would be alternately + and —, changing sign at each half revolution, and leads permanently connected with them would deliver alternating current. The same result would evidently follow if two opposite commutator segments were permanently connected each to a collecting ring on the armature shaft. The number of alternations per minute is evidently 2 *n*, where *n* is the number of revolutions per minute. In a four pole machine the E. M. F. in a given coil would evidently change sign every 90 degs., in a six pole machine every 60 degs. and so on, so that in a multipolar generator the E. M. F. in a given coil would have P *n* alternations per minute, where P is the number of poles.

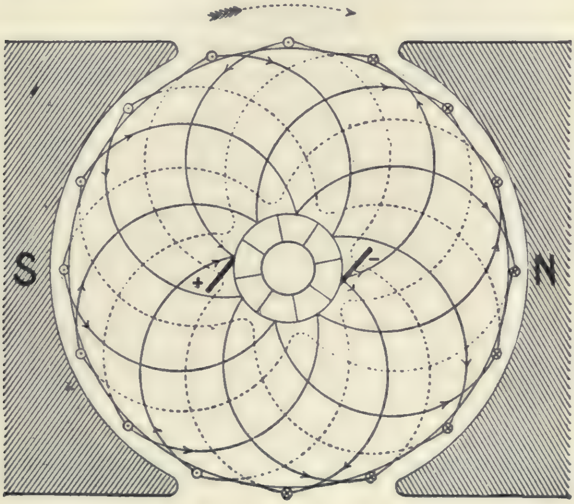
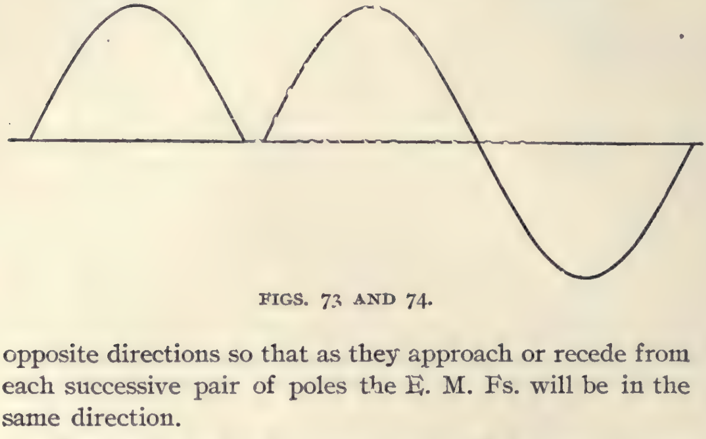


FIG. 72.

If the armature of Fig. 72 were revolving at 1500 r. p. m. and were fitted with collecting rings we could take off from them an alternating current of 3000 alternations per minute. It is often preferable to define this frequency in terms of cycles per second. A cycle is the period from a given E. M. F. to a second E. M. F. in the same direction. If Fig. 73 shows a single alternation of current, then Fig. 74 depicts a single cycle. To reduce alternations per minute to cycles per second, divide by 120. Thus the current delivered by the armature of Fig. 72 connected as an alternator would be of twenty-five cycles (~) per second. In designing alternating generators for high voltage it is desirable to have all the armature conductors in series, so that the armature winding is arranged with that in view. The usual procedure is to wind alternate armature coils in opposite directions so that as they approach or recede from each successive pair of poles the E. M. Fs. will be in the same direction.



FIGS. 73 AND 74.

Inasmuch as the frequency employed in power transmission work is quite often as high as 60 ~ it is evident that either the speed must be high or there must be a considerable number of poles. The result of arranging a generator to meet these conditions is the production of a highly specialized type of alternator apparently quite distinct from ordinary continuous current dynamos. As a matter of fact most of the latter class can be made into fair alternators by the proper connection of collecting rings, as already shown, but very few alternators could be made to give continuous current successfully by the addition of a commutator. Fig. 75 shows the general type toward which modern alternators tend. It is a 60 k. w. Westinghouse generator giving a frequency of 60 ~ at 600 r. p. m. This size is wound on occasion for voltage as high as 5000. The armature coils, one per pole, are machine wound on forms, heavily insulated and sprung into slots in the armature core. This simple type of generator has been in use for several years past in connection with a 10,000 volt line from raising transformers, for sending current twenty-eight miles from San Antonio Canyon to San Bernardino, Cal. Like all other generators, the alternator is reversible and can be used as a motor. In this function, however, it possesses some curious and interesting properties which will be discussed later.

The most characteristic property of alternating current is its potency in producing inductive action. Such action depends on changes of magnetic field, which in turn depend on variation of the magnetizing current, and an alternating current is in rapid and continuous variation all the time.

It is this property which gives alternating current its immense advantages in power transmission, since it enables changes of voltage to be made very simply and with very trifling loss of energy, and changes of voltage are absolutely essential to economical transmission over long distances.

From our original formulæ for figuring wiring it at once appears that for a given percentage of energy lost in the line, the area of copper necessary varies inversely as the square of the working voltage. For doubling the working voltage halves the current corresponding to a given amount of energy, while for the same percentage of loss it doubles E, which appears in the denominator of the formulæ. The value of even a small increase of working voltage appears in the most striking manner in the table of Chap. IV. For working circuits the voltage is limited to such a figure as permits of thoroughly successful insulation of the motors under service conditions. In the transmission the limit is imposed only by the conditions of safe insulation of the line and the generator or transformers, which is a very different matter.

Hence while for railway motor service most of the work has been at about 500 volts, and 1000 volts appears to be the extreme limit in the present state of the art, alternating power transmission lines are very generally worked at from 4000 or 5000 volts up to 10,000 or much more. The transmission of power to the Oerlikon works near Zürich, Switzerland, has been steadily operated for several years at about 14,000 volts on the line, while those at San Bernardino, Sacramento, and Fresno, Cal., are operated at from 10,000 to 11,000 volts. This means that the line copper required is less than one per cent of that which would be needed for direct feeding of the motors at the same percentage of loss. For railway work in distributing power to substations nothing less than 5000 volts is likely to be used and 10,000 will be frequent. At distances at which substation working becomes economical less than 5000 volts will hardly pay. We have already seen in the preceding chapter that on anything less than a fifteen or twenty mile road, transmission to sub-stations is not likely to compete advantageously with the ordinary device of separate stations. At such distances 10,000 volts is to be recommended as a standard pressure.

The problem of getting such voltages is not altogether simple. The most usual method is to generate the power at a rather moderate voltage, say, 500 or 1000, and then to obtain the high line pressure from raising transformers. For voltages of 10,000 and upwards this is by far the best plan, and so indeed it is generally for 5000 volts, but for pressures up to the last mentioned figure and even above it, there is a strong tendency to construct special high voltage dynamos feeding directly into the line. This avoids the cost of the raising transformers and the loss of energy incurred in them. On the other hand such high voltage dynamos are rather difficult and expensive to construct and somewhat more liable to deterioration than those of lower voltage. While it is possible to wind alternators in the ordinary manner for pressures of 5000 volts or so, the thorough insulation of the moving armature becomes a very difficult matter.

Under these circumstances it is far better to design the generator in such wise that the high voltage armature wires shall be stationary, and the field magnet then becomes the moving part of the machine.

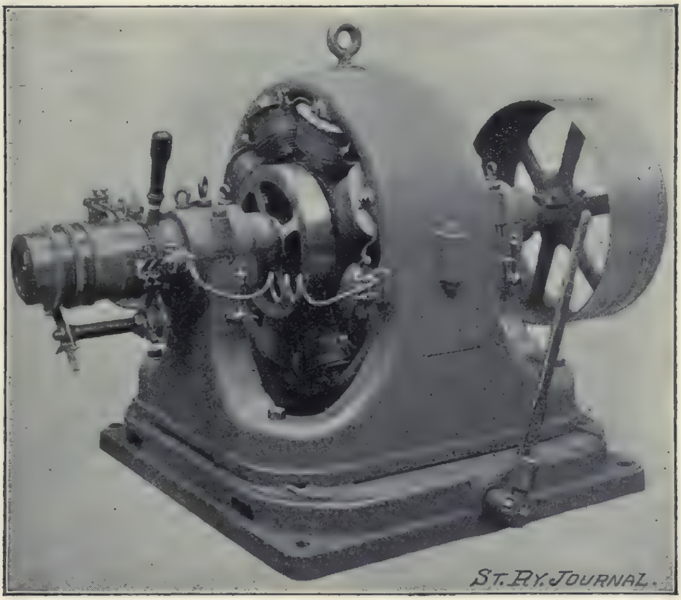


FIG. 75.

The commonest way of arranging such a generator is to place the armature coils in slots cut in the inner face of a laminated iron ring and to revolve within this ring a star shaped multipolar magnet, occupying the position of the armature in Fig. 75. Such a generator is shown in Fig. 76. The proper insulation of the armature coils is here comparatively easy and the chance of their breaking down is very much reduced. It should be remembered that 5000 volts will actually spark across an air space of about ⅛ in., and the power of such a pressure to break down insulation is most formidable. If in addition to so great an electric strain the armature insulation has to stand prolonged vibration and centrifugal strain its life is likely to be somewhat uncertain. For these high voltages therefore a machine with a stationary armature is much to be preferred to the ordinary types, especially since the latter have no compensating advantages.

FIG. 76.

Another and a very ingenious form of generator with two phase stationary armature is shown in Fig. 77. Here the armature is composed of two laminated rings placed side by side in a common frame a short distance apart. Each is slotted to receive heavily insulated rectangular coils as shown in Fig. 78. The revolving part of this machine, is simply a steel casting furnished with a set of outwardly projecting laminated pole pieces at each end. The field winding is a single fixed circular coil around the field between the two armature rings. The armature current is taken off from fixed binding posts instead of brushes, just as in the generator shown in Fig. 76, but in this latter machine there are not even brushes for the field current or any other purpose. These inductor dynamos may be safely wound for as high as 5000 volts even in machines of moderate size.

With 5000 volts available at the terminals the transmission of power over moderate distances can be effected more cheaply than by the use of higher voltages derived from raising transformers. The economics of the question involve no difficulties. The cost of raising transformers and their accessories in ordinarily large units may be taken as on the average about $10 per kilowatt of output. At 10,000 volts, the pressure generally used when raising transformers are employed, the cost of copper is but one-fourth that required for transmission at 5000 volts and the same loss. The latter has the advantage of greater

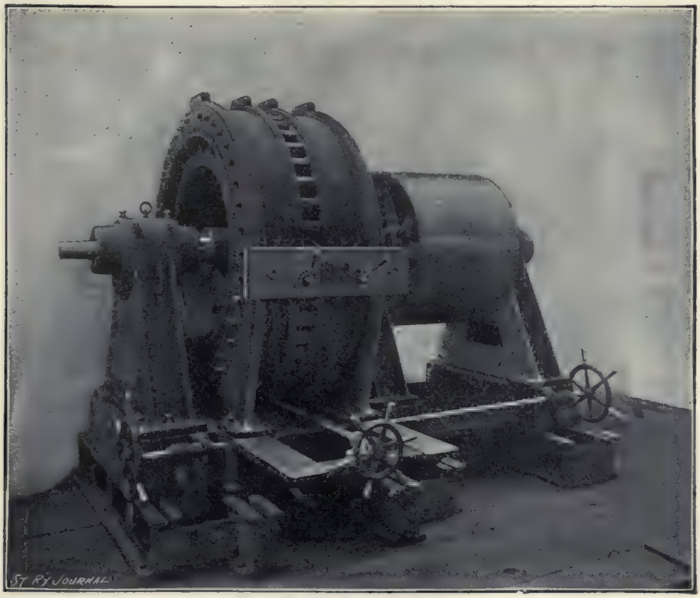


FIG. 77.

efficiency by the loss in the raising transformers, say, two per cent, and the depreciation of the line copper is less than that of the transformers. On the other hand the depreciation in the high voltage generators is somewhat greater than in the low voltage ones. Setting these respective qualities off against each other we can say for an approximation that the cost of transmission becomes equal by the two methods when three-fourths of the cost of copper for transmission at 5000 volts amounts to $10 per kilowatt delivered. The distance usually corresponding to this condition is ten or twelve miles. In sizes from 250 k. w. up, stationary armature machines are now built for as high as 10,000 to 12,000 volts. They are reliable, cost considerably less than low voltage machines with transformers, and are equally or more efficient. Where 10,000 or 12,000 volts is sufficient they give admirable results and are coming into extensive use.

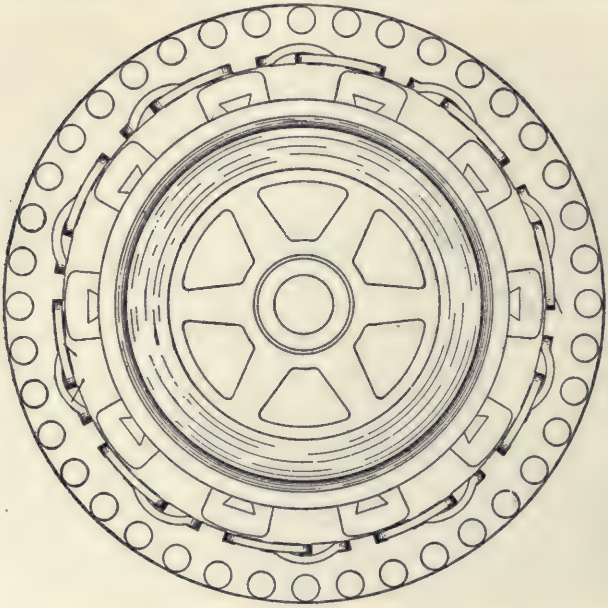


FIG. 78.

One cannot well theorize on this matter, however, since the prices of copper and apparatus are subject to frequent variations and in actually making contracts these variations are very arbitrary in character. It is sometimes for the interest of a bidder to cut prices on some particular arrangement of apparatus or to raise them on another, quite overturning the buyer's preconceived notions on the subject.

The transformers used in this heavy transmission work are very different in appearance from the familiar little ones that decorate the poles of electric lighting companies, although, of course, identical in principle.

The output of an alternating current transformer, the general features of the design remaining the same, would naturally, save for the question of heating, increase rather faster than in proportion to its aggregate weight of copper and iron. But, other things being equal, the weight increases as the cube of the linear dimensions, while the surface increases only as their square. Hence the heat into which the energy losses in a transformer are converted has less chance to escape by radiation in a large than in a small transformer, the available surface area per watt being much reduced. Therefore unless there are special precautions taken the large sizes will run too hot and endanger the insulation.

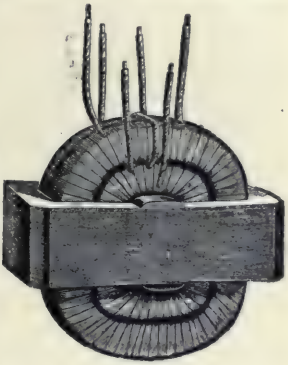


FIG. 79.

So the ordinary small transformer, of which the core and coils are shown in Fig. 79, cannot be indefinitely increased in size without taking care to provide means for compensating the lack of proper radiating surface for getting rid of the heat.

There are several methods of doing this. One of the best is by filling the transformer case with oil. This by its mere presence in the case assists in transferring the heat from the core and coils to the case whence it can be radiated, and may increase the possible output for the same heating by ten per cent or more. In large transformers it is usual to go further and to cool the oil artificially either by a worm through which cold water is kept circulating or by circulating the oil itself through a cooling worm.

An excellent example of the former practice is shown in Fig. 80, which is a 100 k. w. Westinghouse substation transformer taken apart to show the construction. The case is an iron cylinder, in which the core and its coils are placed. The case is then filled with paraffine oil. Just inside the case, between it and the coils, is the cooling worm of galvanized iron through which a constant stream of cold water is kept flowing. This keeps down the temperature so that a large output can be obtained without loss of efficiency. For the efficiency depends on the ratio between the output and the sum of the losses in the core and the coils. The losses in the former are nearly constant, so that if they form a considerable portion of the total loss the efficiency may even increase with increase of output.

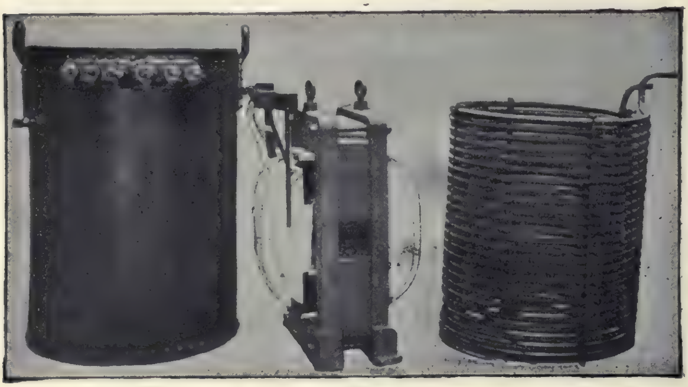


FIG. 80.

Another equally effective method of obtaining a high output without overheating is by building the transformer core of bunches of iron laminæ separated by air spaces of ¼ in. to ½ in., subdividing the coils in a similar manner, and then forcing through the whole structure a stream of cool air from a small blower. This construction both keeps the transformer cool and by subdividing the primary and secondary coils renders it easy to insulate for high voltages.

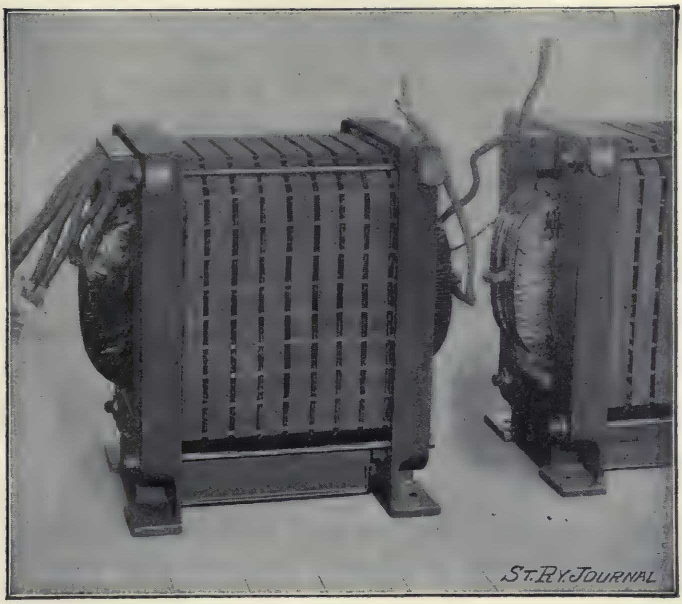


FIG. 81.

Fig. 81 shows a large substation transformer made in the fashion just described, stripped of its connections and external casing so as to be more easily seen. The coils are wound rather deep and thin and the primary and secondary sections alternate with heavy insulation between each section. The cooling blast is introduced from the bottom. Channels for the air are arranged under each transformer and a small motor blower furnishes the blast, a single horse power being ample to supply the air for cooling transformers of some hundreds of kilowatts capacity.

Such air cooled transformers are capable of giving a large output for their weight and a very high efficiency. The average weight runs about twenty to twenty-five pounds per kilowatt of output, while the efficiency reaches and sometimes exceeds ninety-eight per cent.

There is no difficulty in constructing these large substation transformers to give 10,000 volts or more from the high voltage coil and their construction is such that they are little subject to accident. The air blast transformers separate the primary and secondary coils by air spaces and heavy mica insulation, while those in which oil is employed add its very high insulating properties to those already obtained from the construction of the transformers. Either type is thoroughly reliable for substation working. These high voltage transformers should always be placed in a room by themselves, out of reach of all save the employes whose regular work it is to care for them, for 5000 to 10,000 volts means danger and should be treated with due respect. At such voltages no ordinary insulation is any guarantee of safety and bare wire which bears evidence of danger on its face is quite as desirable as any insulated wire.

Perhaps the best plan for taking care of extreme voltages in generating or substations is to isolate them and keep them out of reach as far as possible, using switchboards with no exposed wiring on their faces. What wiring is necessary should be on porcelain insulators, not crowded, and perfectly accessible when occasion demands, but not otherwise. Particular care should be taken to have the course of high tension wires obvious at a glance, avoiding all involved connections, so that it will be possible to trace at once every such wire from its origin at the high tension terminals of the transformers through the switchboard, if there be one, and safely out of the building to the line.

Bear in mind that for the sake of simplicity, economy and efficiency, the transformer units should be few in number and of large size rather than many and of moderate size. When, however, the individual transformers can be of considerable output, say, fifty to one hundred kilowatts, further increase in size is less important, for beyond such outputs the increase in efficiency and decrease in relative cost is much slower than the variation in smaller sizes. The increase of efficiency in passing, for instance, from a ten kilowatt transformer to one of one hundred kilowatts is about 2 to 2½ per cent, while in passing from a one hundred kilowatt transformer to one of 500 to 1000 k. w. the increase in efficiency is decidedly less than one per cent.

With respect to the treatment of high voltage transmission wires after leaving the stations, much might be said, but since ordinary precautions for high voltage are obvious to the engineer it is sufficient to emphasize a few points dictated by experience.

As to poles, as in many other matters, in the long run the best is the cheapest. Clean selected cedar is by far the best material available in this country. The poles for power transmission work should be somewhat longer and stronger than usual, for they have to carry substantial wires, often through open country where the wind has full sweep. The length should be great enough to keep the wires well out of the way and to permit carrying the lines easily over ordinary circuits when crossing is absolutely necessary. A good standard is a forty foot pole with a seven inch top, set fully six feet in well tamped earth. Now and then for runs across clear country thirty-five foot poles may well be used, but the tops should generally be seven inches, and the setting about five feet six inches deep. The poles should run not less than about fifty to the mile. Such a line may appear needlessly heavy, but inasmuch as continuity of service depends on the integrity of the line, the precautions are well taken. For the same reason the cross arms should be extra strong and secured to the poles with special care.

The matter of insulators is of the utmost importance. Up to 4000 or 5000 volts large, strong, double petticoat, glass insulators will give good results. Such insulators have been in use on arc circuits of similar voltage for years with uniform success. Glass insulators of special construction with extra deep petticoats have been successfully employed with even 10,000 volts alternating. A pole head equipped with such insulators is shown in Fig. 82. This is the type of insulator used in the San Antonio Canyon plant, to which reference has been made.

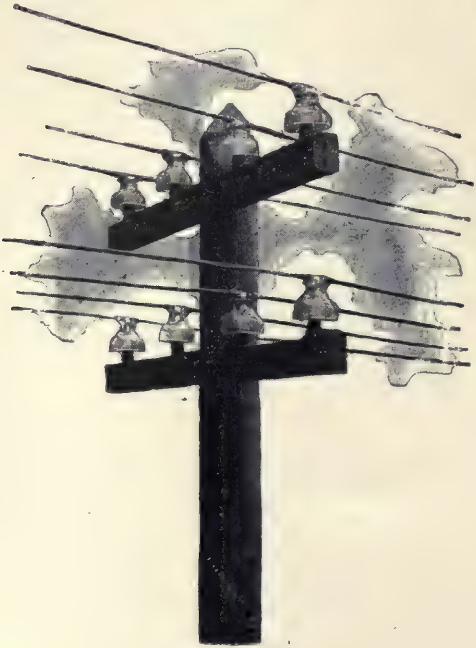


FIG. 82.

At so high a pressure, however, porcelain is much to be preferred, owing to its higher insulating properties, particularly after protracted weathering, and to its great mechanical strength. It should be distinctly understood that poor porcelain is worse than glass and that to be effective as an insulator the porcelain must have not merely a surface glaze, but must be strongly vitrified clear through.

A good test of quality is to chip through the external surface and place the point of a well filled pen on the break. If the ink flows and produces a spreading stain, and particularly if it works under the exterior glaze, the porcelain is probably worthless as an insulator. Much cheap porcelain is somewhat hygroscopic and in a damp climate is utterly worthless.

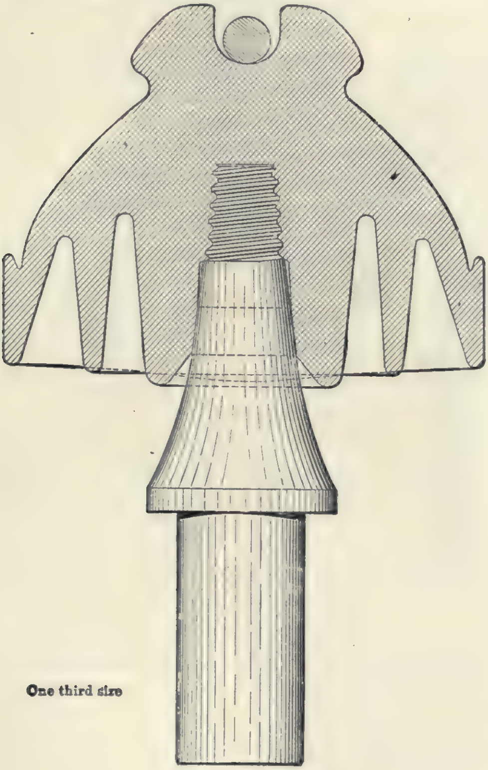


FIG. 83.

First class porcelain, however, is an ideal substance for insulators on all long, high voltage lines. For this purpose the insulators should all be tested and should not break down at double the normal voltage.

An excellent specimen of these high grade porcelain insulatiors is shown in Fig. 83. This particular form was developed for the Niagara-Buffalo transmission line in which a voltage of 20,000 is designed to be used. The insulators were tested at 40,000 volts and very few had to be rejected for failure. They depend for their insulating power on the quality of the porcelain and on well designed double petticoats. Such insulators are admirably adapted for work up to at least 20,000 volts, provided the climate is reasonably good. In very moist climates where the insulators are exposed to frequent searching mists and nearly constant dampness still further precautions are desirable, and these excellent results can be secured by using oil insulators of which a very good specimen is shown in section in Fig. 84. The pin, P, of iron, is cemented into the body of the insulator, I, which is made thick and solid. The thick bell of the insulator is turned inwards and upwards at its lower edge so as to form a circular cup, C. This cup is filled with highly insulating oil, which is exceedingly efficient in stopping leakage along the surface of the insulator to the iron pin. In dry and dusty weather, however, the oil accumulates dirt and is likely to be reduced to a species of mud, quite destroying its insulating value. The oil insulator seems to be passing out of use, but for very high voltages in damp climates it has merits.

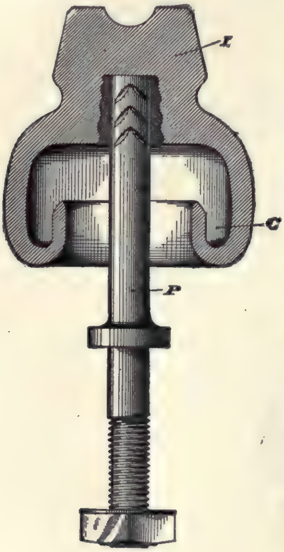


FIG. 84.

With respect to the general arrangement of a transmission line too much care can hardly be taken in keeping the circuit away from danger of accidental contact to persons and things. Bare wire is preferable to insulated since it does not encourage a feeling of false security, and it should be distinctly understood that the wires are dangerous and must be let alone. Particular pains should be taken to carry the wires clear of other circuits, arranging guard wires for their mutual protection whenever they can do good. If the circuit runs through a wooded region the branches of trees and all dead wood should be cleared away so that nothing can sway against or fall upon the transmission wires. The wire itself should be jointed when necessary with unusual thoroughness, and should be inspected at the original joints if such there are. It is one advantage of bare wire, that there is no covering to hide careless joints. The line as a whole should be easily reached for inspection or possible repairs. If it does not run along the track it should follow a public road or good pathway so that any point can be quickly reached by wagon or bicycle.

Up to this point we have been dealing with principles common to all alternating transmission systems irrespective of particular characteristics. As a matter of fact ordinary single phase alternators are seldom used at present for transmission purposes. Although the single phase alternator is, like other dynamos, reversible and can readily be used as a motor, inability to start as a motor is perhaps its best known characteristic. This makes it singularly inconvenient for most purposes, and while the difficulty can be overcome by using induction instead of synchronous motors, single phase induction motors are not satisfactory for large powers and cause a heavy inductance on the system that is troublesome in more ways than one.

For railway distribution it is at present generally necessary to convert the transmitted energy at the substation into the form of continuous current. The means taken to do this are quite various, but they all involve the starting of rotary apparatus, virtually of motors, whatever their function may be ultimately. So the problem of utilizing an alternating transmission for railway purposes begins with the task of starting a synchronous alternating motor. There have been many ingenious plans devised for this purpose, some of them depending on the action of a commutator during the period of getting up to speed. The only device practically used in this country, however, is the rather obvious one of bringing the synchronous motor up to speed by means of an alternating induction motor, and then cutting out the latter, leaving the former to run in synchronism and take up its load from a clutch.

This arrangement while perfectly applicable for substation work has been largely superseded for all purposes by polyphase motors, which start easily and unassisted under their own torque.

The general principles of the polyphase systems are at the present time sufficiently well known to engineers to render detailed explanation here unnecessary. By polyphase it is here intended to designate all alternating systems employing two or more alternating currents displaced in phase in a uniform and systematic way. Practically there are two species of this genus, one having two alternating currents 90 degs. apart in phase, the other having three currents 120 degs. apart in phase. There are several varieties of each, but it may be stated broadly that for the practical purpose of transmitting power to substations for railway purposes, both the species and their varieties are substantially equivalent. From an academic standpoint wide differences may be pointed out, and in certain branches of polyphase work the differences may be worth considering. The three-phase system has the important advantage of saving 25 per cent of the line copper, for the same maximum voltage between wires. But as a two-phase current is very easily changed into a three-phase one and back again in the raising and reducing transformers, the type of apparatus used makes little difference in the net result. Practically this change is nearly always made on long transmission lines, so that one gains the advantage of the saving in copper, whether three-phase or two-phase machines are actually used in the stations. So far as the railway engineer is concerned these differences are practically negligible.

Of course, polyphase apparatus is closely similar to that used for ordinary single-phase work in general arrangement. The principal differences are to be found in the armature windings. Two phase dynamos and motors customarily have two separate windings on the armature, displaced 90 degs. with reference to their spacing between consecutive poles. This kind of winding with its overlapping coils is admirably shown in the Stanley two phase machine shown in Fig. 78. Three phase generators are similarly arranged except that there are three sets of coils usually spaced 60 degs. apart, one set being reversed

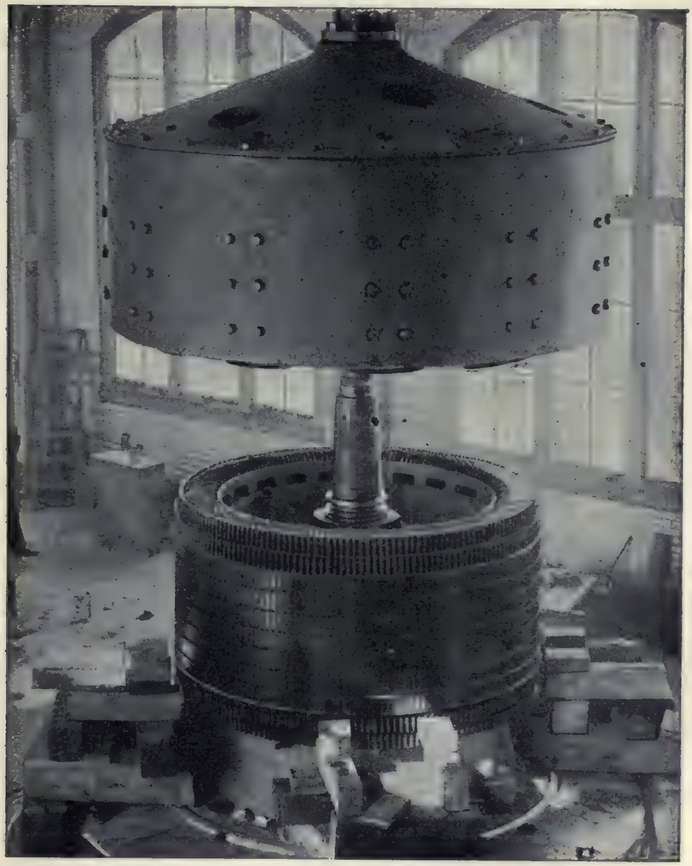


FIG. 86.

to give the requisite 120 deg. phase difference. The windings, are, for convenience or for special purposes, variously modified in different machines, but the general arrangements are as just indicated.

Polyphase generators as a class give a rather better output for their weight than single phase machines, owing to a better utilization of the armature space by the distributed windings. As a rule, too, they represent later and better ideas in design, hence are apt to be more efficient and to regulate better than ordinary alternators. Perhaps the best example of the two phase type is to be found in the huge 5000 h. p. Niagara generators, one of which is shown in Fig. 86 during the process of assembling, with the field ring ready to slip into place. The stationary armature has its coils set in deep slots in the laminations and is provided with ample ventilating ducts. The armature winding does not consist simply of one coil per phase per pole as shown in Fig. 78, but each phase winding consists of a number of coils in adjacent slots, thus occupying the armature surface to better advantage. Such a construction is very often employed in large polyphase machines.

The revolving field is here external to the armature, so that its weight gives the effect of a gigantic flywheel. The commercial efficiency of this generator at full load is almost exactly ninety-seven per cent, a figure due to the combination of careful design and immense size. These Niagara generators are probably destined to play a very important part in the development of electric railroads over a radius of many miles.

Machines with vertical armature shafts are rather rare in American practice, the ordinary horizontal arrangement being more generally convenient. Hence the usual type of polyphase generator is not that found at Niagara, but is more nearly akin in appearance to familiar forms. A thoroughly typical example of recent practice in three phase generators is shown in Fig. 87. This exhibits the dynamo room of the three phase transmission plant at Folsom, Cal., containing four 750 k. w. generators. These machines run at 300 r. p. m. and deliver current at about 800 volts and

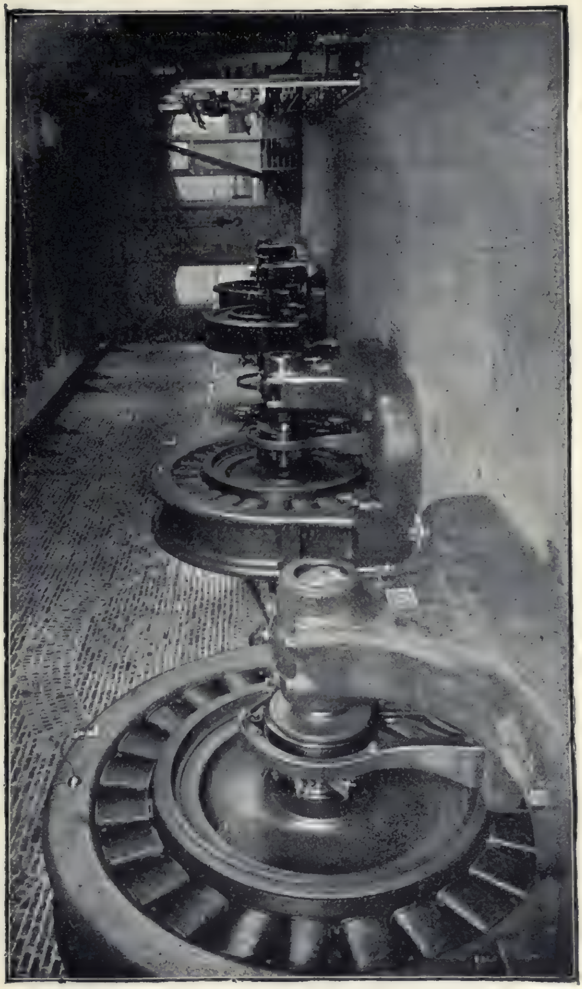


FIG. 87.

60 cycles per second. The armatures are built, like those of the Niagara generators, with several slots per phase per pole, so that the armature inductance is very low and the

variation in voltage with change of load almost negligible. The machines are primarily intended for direct coupling, as is generally the case with dynamos of so great output, and in this case they are connected to double horizontal turbines working under a head of about fifty feet. The shafts pass through close fitting sleeves to the exterior of the power house where the turbines are located. The transformers of the air ventilated type already described are located above the dynamo room and serve to raise the line pressure to nearly 11,000 volts for transmission twenty-three miles to Sacramento. The four generators are operated in parallel, as is the case with most plants in which modern polyphase apparatus is employed. It should be noted that such parallel running is very easy if the generators are so designed that they have good inherent regulation. The commercial efficiency of the Folsom machines is about ninety-six per cent at full load.

Generally speaking these and other polyphase machines are characterized by higher efficiency, lower inductance and enormously better regulation than is to be found in any of the older alternators. The value of the two latter characteristics for power transmission on a large scale can hardly be overestimated.

The efficiency of these modern generators is subject to some variation according to size and speed, but between different makes of the same size, speed and voltage the differences are small. The following is about what can be counted on at full load from polyphase generators of various sizes:

Output in k. w.	Efficiency per cent.
50— 100	92—93
100— 200	93—94
200— 500	94—95
500—1000	95—96

This supposes moderate voltages, say, not exceeding 4000 in the larger machines or 2000 in the smaller. It also supposes the speeds to be fairly high—not below 500 r. p. m. for the sizes up to 200 k. w., and not below, say, 200 for the larger sizes. Slower speeds and higher voltages than those mentioned are very likely to reduce the efficiency by one or two per cent, even more for small sizes running at unusually low speeds. If the prime mover is of low speed, such, for example, as a Corliss engine, it is quite easy to lose more in efficiency by using small direct coupled generators of, say, 100 k. w. or less, than would be lost by belt driving.

Inasmuch as practically all railway work is at present done by continuous current, the energy received at any substation, transmitted by alternating current, simple or polyphase, must be changed into continuous current for use on the working circuit. There are various ways of effecting this transmutation, all of them, unfortunately, quite inefficient compared with the results obtained from static transformers, and what is worse, all requiring attention which, however slight, cannot be dispensed with.

The most obvious plan is to employ a motor driven from the alternating circuit by belting or coupling it to a continuous current dynamo. Such is the simplest and often the cheapest method when existing stations are to be converted into substations operated from a transmission plant. The engine can be removed or merely disconnected, and a synchronous motor installed to take its place in driving the dynamos. This is the arrangement which has been used for several years past at Hartford, Conn., and Taftville, Conn., in both of which places the already existing generators were driven from polyphase synchronous motors. The same practice is followed in the Folsom-Sacramento transmission. At the latter place generators for the electric railway and for other purposes are driven from a countershaft which receives its power from three phase synchronous motors. The generator room of the Sacramento substation, which is a typical example of the practice under consideration, is shown in Fig. 88.

Obtaining continuous current in this way is often very convenient, but is most reprehensible from the standpoint of efficiency. It may answer well enough for the utilization of very cheap water power, but for general substation work it should not be seriously considered. Allowing ninety-three per cent efficiency for both generator and motor, which is certainly as high as ordinarily found in practice, and taking the loss in belt and countershaft as

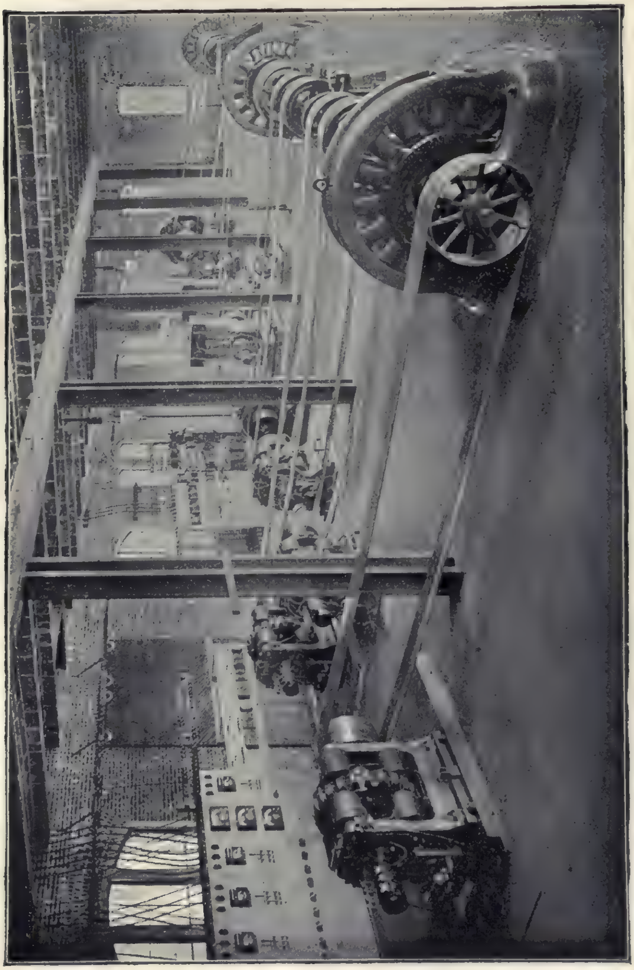


FIG. 88.

ten per cent at full load, which is low, the net efficiency of the combination from the energy received by the motor to that delivered by the generator is only seventy-eight per cent. This loss of twenty-two per cent of the total energy in changing from alternating to continuous current is too considerable to be endured unless under very exceptional circumstances.

An alternative method is the use of a species of composite machine composed of alternating motor and continnous current dynamo assembled on the same base. As the two elements are rigidly in line, usually have one common bearing and are relieved from belt strain, their combined efficiency should be perhaps a couple of per cent better than would be indicated by their efficiencies taken separately. Such composite machines are sometimes used in this country, and not infrequently abroad, chiefly for lighting work. Fig. 89 shows a fine 500 k.w. motor generator, three-phase to continuous current, employed on the great 80 mile, 33,000 volt transmission to Los Angeles, Cal. In units of 200 k. w. or so, such machines should show a full load efficiency of about 88 per cent if properly designed.

Sometimes windings for both kinds of current are put on a single armature core, but this device has little to recommend it.

For railway work by far the best method of obtaining continuous from polyphase current is by the use of the apparatus variously known as rotary transformer or rotary converter. The principle of this machine can be readily seen by reference to Fig. 72. If the armature here shown is put in rotation as an alternating motor by feeding alternating current into the collecting rings and bringing the machine into syncronism by any convenient means, there will evidently be flowing through the armature windings the same sort of current that would be generated if the armature were working as a dynamo. As a dynamo this current could either be withdrawn through the rings as alternating current or through the commutator as continuous current. So when the same current is delivered to the machine from an external source it may be taken off the commutator as continuous current or off the rings as alternating current if continuous current be supplied from the line. The commutator neither knows nor cares whether the current that comes to its leads is generated in the armature or poured into it from a distant source. A small part of the energy supplied is expended in keeping up the rotation of the machine as a motor, the rest is delivered to the line as available current.

FIG. 89.

This device furnishes a very beautiful and efficient method for the conversion of alternating current. It is most available for practical purposes in its polyphase form, since although it works admirably with single-phase current it cannot start as a motor, nor is it able to give quite so good an output. For polyphase work the armature winding is tapped not as in Fig. 72 at two points, but at three or more, so spaced as to divide the windings in such wise that if the armature were worked as a dynamo it would deliver polyphase currents.

Fig. 90 shows the connections of a two pole ring winding tapped for three-phase currents or for working as a three-phase rotary converter. Here leads are simply taken off from three points on the winding 120 degs. apart and carried to the three collecting rings. In this case the machine will come up to speed as a three-phase motor when the field is broken and current thrown on the rings. Many rotary converters, however, require a very large starting current and in starting greatly reduce the voltage of the circuit, so that induction motors are sometimes employed to bring them to synchronous speed, or where several rotaries are used, the machines are generally started from the continuous current side. When at speed the field circuit, which is connected like that of an ordinary shunt dynamo, is made, the armature falls into synchronism with the generator and continuous current may be drawn from the commutator. For two phase currents the leads are taken off in a precisely similar way, but from four points 90 degs. apart on the winding. There are still other and more complicated connections used for multipolar machines and for various practical reasons, but they all embody the same general principles.

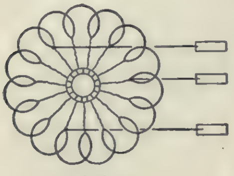


FIG. 90.

As a matter of fact the rotary converter has in efficiency or output an advantage over the same structure used as a dynamo since, as inspection of the winding will show, the average loss in the armature is lessened, because the current does not at all times have to traverse the full extent of the winding between ring and ring.

An excellent example of modern practice in the rotary converter line is the Westinghouse two phase machine shown in Fig. 91, designed especially for railway substation working. As a generator it can deliver either two phase or continuous currents or both, or when two phase current derived from reducing transformers is supplied to the collecting rings, continuous current at from 500 to 550 volts can be withdrawn from the commutator. The striking similarity between this and an ordinary railway generator is at once apparent, and in practical properties the two machines are almost identical. In fact the earliest rotary converters were made by adding rings to standard generators, but of late some modifications have been found useful. The three phase rotary converter has already been shown in connection with the Lowell plant.

All rotary converters require alternating current of less voltage than the continuous current derived from it.

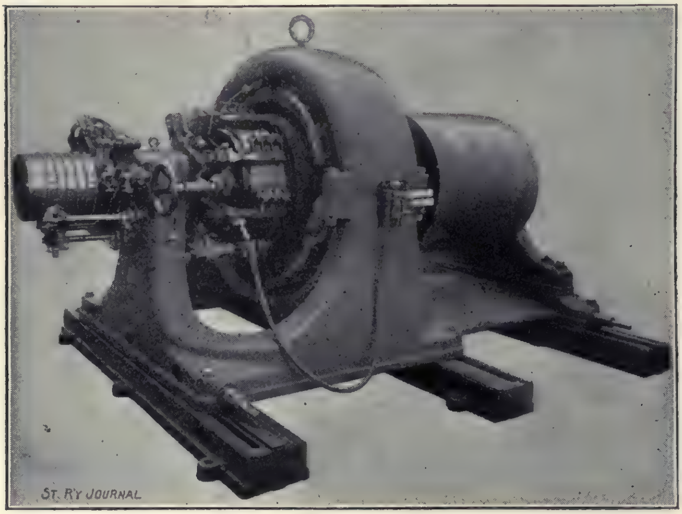


FIG. 91.

The exact voltage varies with the number of phases used and with the field excitation of the converter. In the two and three phase machines ordinarily used the alternating voltage ranges from 300 to 375 for a continuous voltage of 500 to 550.

The efficiency of conversion by this means is very high, at least as great as would be obtained from standard railway dynamos of similar size and speed, and the converters as a rule work admirably. If the voltage per commutator segment is kept within conservative limits and the armature inductance is moderate, converters give no trouble from sparking and require very little attention. They are usually for rather low frequency, twenty-five to thirty-five cycles per second, owing to the fact that a higher frequency necessitates a rather complicated commutator in order to keep the volts per bar sufficiently low, and this condition makes the design of the armature somewhat embarrassing, especially in very large low speed machines.

As in the case of synchronous alternating motors, the strength of the field in a rotary converter has a profound influence on the voltage of the alternating line and can cause the current therein to lag or lead by a considerable amount. The proper adjustment of the field strength is a very important matter. It should be so arranged as to keep the line current as nearly in phase as possible, which is probably best accomplished by using generators and converters of low inductance and compounding them.

The rotary converter is the best means at present available for obtaining continuous from alternating currents. Its weak points are the close interdependence of the alternating and continuous voltages, and the necessity of using quite low frequencies. For certain cases the combined synchronous motor and generator, in principle like Fig. 89, may be advantageous, but for all around working, the rotary converter is generally preferred.

Power transmission lines for alternating current require rather more care in computation than do continuous current lines, for one has to deal with the phenomena of inductance in line and load, and the resulting "false current" which may compel the delivery of a current greater than is indicated by the energy concerned.

In the general problem of power transmission these considerations are most troublesome, but when the principal work is the operation of substations for railway purposes, which is the case in hand, it becomes comparatively simple.

For since changing the excitation of a synchronous alternating motor shifts the phase of the line current, this excitation can be adjusted so as to neutralize the inductance in circuit and leave the line current nearly or quite in phase with its E. M. F.

As the motor field is gradually strengthened, the current lags less and less, the apparent energy comes to approximate more closely the real energy, and the current on the line consequently grows smaller. When the lag disappears the apparent energy (i. e. volts multiplied by amperes) coincides with the real energy, and the line current is a minimum. As the motor field is strengthened still more, the current begins to lead the E. M. F., the apparent energy increases, and the line current also increases.

It is desirable to keep the power factor of the circuit (i. e., the ratio between real and apparent energy) as near unity as possible, since when this condition is fulfilled the energy delivered per ampere of line current is a maximum, and all the apparatus gives its best performance. Hence, the field of the motor or converter should be kept at such a point that the line current for normal output, as shown by the ammeter, shall be a minimum.

As the output varies, the current will lag or lead somewhat, but if the output for which the lag vanishes is properly chosen, the power factor at all working loads will still be high, say, within ten per cent of unity.

The net result of the adjustment of the motor field with reference to the inductance in circuit is practically the maintenance of a power factor very near unity under all normal conditions, so that the circuit behaves almost as if it were carrying continuous current. Except for a small allowance for changes in the power factor the line may be computed much like a continuous current line. In fact the formulæ of Chap. I may be used unchanged for figuring single phase and two phase transmission circuits, assuming that C in these formulæ equals the watts delivered divided by the voltage of delivery, as with continuous current.

If, for example, we wish to deliver 450 k.w. 100,000 ft. from our station, using 10,000 volts on the line with ten per cent drop, the equivalent current is fifty amperes and we may proceed as follows:

From formula (1) Chap. I

$$c.\ m. = \frac{11 \times 50 \times 200{,}000}{1000} = 110{,}000.$$

This gives the size of wire necessary for a single phase circuit. If the circuit is two phase, half of the energy is sent over each circuit, which must be then of 55,000 c. m. wire.

From formula (5)

$$W = \frac{33 \times 50 \times 40{,}000}{1000} = 66{,}000 \text{ lbs.}$$

This amount is the same for both the two phase and single phase circuits, in the way usually employed for operating two phase circuits, i. e., a complete and independent circuit for each phase. Sometimes the two phases have a common wire which modifies the amount of copper required, but this method of interconnection is seldom used on a large scale, since on long lines and at high voltages it involves serious practical difficulties.

The three phase system requires a special, though very simple, calculation for the line. As ordinarily installed the three phases are mutually interconnected, so that the line consists of only three wires. This combination of circuits so utilizes the wire that for a given amount of energy delivered with a given maximum voltage between lines and at a given loss, the copper required is just seventy-five per cent of that necessary for an equivalent single phase line.

This means that since the three phase line consists of three equal wires stretching from station to station, each of these wires must be of half the cross section needed for a single phase line wire under similar circumstances. If the single phase line consists of two wires each weighing 1000 lbs. per mile, the three phase line will consist, for the same loss, of three wires each weighing 500 lbs. per mile.

There are, of course, divers ways of taking account of this saving in the formulae, but the author has found the following to be the most convenient and direct. Write in (1) $\frac{W}{V}$ for C, and D, the distance between stations, for L. Then

$$c.\,m. = \frac{11 \frac{W}{V} D}{E},$$

E being as before the loss in volts, while W is watts delivered and V voltage of delivery.

Applying this formula to the example just given we have

$$c.\,m. = \frac{11 \times 50 \times 100{,}000}{1000} = 55{,}000.$$

This is the area of each of the three wires. Similarly for the total weight we may modify (5) and multiply by 3, giving for a close approximation the exceedingly simple form

$$W = \frac{100 \frac{W}{V} D^2{}_m}{E}$$

Applying this to the case in hand we have

$$W = \frac{100 \times 50 \times 10{,}000}{1000} = 50{,}000 \text{ lbs.}$$

A very simple formula for approximate cost is

$$P = \frac{p\, D^2{}_m \frac{W}{V}}{E}$$

wherein P is the total cost in dollars and p the current price of bare copper in cents per pound.

These formulæ for alternating transmission circuits enable the economics of the matter to be investigated very rapidly. In the final design of the line it will usually be found, as in the case given, that the size of wire will fall between two standard sizes. In this case, as a rule, select the nearest size and figure out the final amount of copper from the actual weight of this wire.

If the excitation of the motor or rotary converter fields is properly adjusted no account need be taken of in ductive drop, since the widest departure of the power factor from unity will not in any practical case be great enough to disturb the working voltage seriously.

The only time at which inductance is much in evidence is during the periods of starting the motors or rotary converters. For the best results the generators should have good inherent regulation so that lagging current will not reduce the voltage seriously and it is well to raise the initial voltage a little at the time of starting. Rotary converters when thrown into action may assume either polarity, but a few tentative touches of the switch with small current will secure an E. M. F. in the right direction or better, one may start them from direct current.

Both polyphase generators and rotary converters operate well in parallel, behaving, in fact, much like continuous current generators, when they are once in adjustment. The process of throwing alternators in parallel is very simple if one remembers that the currents must be in phase as well as of the same voltage at the moment of connection. The former condition is determined by phase lamps, the latter by the voltmeters.

For general transmission for railway work the voltage should generally be from 5000 to 10,000, more often the latter. In favorable climates even higher prēssures may be safely employed. The best field for such power transmission is in cases of distribution over distances of fifteen miles and upwards under circumstances in which a specially favorable spot can be selected for the main generating station.

When alternating motors can be conveniently employed on the cars, transmission from a central station at high voltage may become the rule instead of the exception, for with power delivered to the working conductors from static transformers requiring no attention there will be less excuse for long and heavy feeders. In the next chapter we will consider the application of alternating motors to service on cars and the relation of this practice to the development of long distance electric lines.

CHAPTER VII.

ALTERNATING MOTORS FOR RAILWAY WORK.

A vast amount of money, time, and ingenuity, has been spent in attempts to develop motors for alternating current good enough to replace continuous current motors in all their varied uses. These attempts have led to many failures, but through them all we have come at the present time to a very gratifying measure of success. But railway service is on the whole the severest work to which any motor can be put, for it involves severe strains in starting, heavy loads on grades, constant and severe shocks and jarring, and exposure, usually, to dust and moisture. Beyond this a railway motor must be easily reversible, and must be able to work week in and week out without close attention or frequent overhauling.

Until very recently these difficulties have deterred engineers from any serious attempts to put into use alternating motors, but the development of electric railway systems into conditions that demand the methods and apparatus of long distance power transmission has forced the alternating motor into consideration. We have just seen the nature of substation distribution for continuous current railway motors, and to tell the truth it leaves much to be desired. The losses of energy incurred in passing from alternating to continuous current are at best rather serious, the apparatus for the purpose is a very considerable item of expense and, what is worse, a substation with rotary converters requires constant attention, so that the cost of attendance, to say nothing of repairs and depreciation on substation equipment, makes transmitted power so expensive as to bar it from the general use which it finds when not necessarily distributed in the form of continuous current.

Power transmission to rotary converter stations is therefore under existing conditions of limited applicability, for purely financial reasons.

With an available alternating motor for use on the cars the matter puts on a very different aspect. Reducing transformers would be placed at suitable intervals along the line, supplied with energy from high tension feeders and feeding the working conductors directly from their secondaries. The rotary converters or equivalent machines, with the accompanying apparatus, the substation itself and all the attendance would be dispensed with. In addition, the energy lost in conversion to continuous current—from ten to twenty per cent of the whole—would be saved. Assuming one hundred kilowatts average output in the substation, working twenty hours per day, the actual saving would amount to not less than half a cent per kilowatt hour, $36.50 per kilowatt per year. The abolition of this charge for the conversion of energy to continuous current would make power distribution from a central station pay in a large number of cases where boosters or separate generating stations are now the most economical methods available.

Furthermore it would make it possible to employ water power far more freely than is at present worth the while, and would give a particular impetus to long interurban and cross country lines now hampered by the heavy cost of transmitting the necessary power.

Admirable as is this outlook we must not for a moment lose sight of the fact that before entering this promised land we must have an alternating motor substantially as efficient and durable as the present standard railway motors.

It is not, however, necessary that there should be any striking similarity in appearance or in methods of operation between the two types of motor, or even that the alternating motor should be suited to all conditions under which continuous current motors are now worked. Alternating and continuous currents have found for themselves distinct fields of usefulness in electric lighting—why not also in electric railroading?

Out of the motley throng of alternating motors four types are fairly possible for application to railway practice. Each is characterized by a combination of good and bad qualities somewhat difficult to evaluate in the present state of our knowledge of alternating railway work. We may tabulate the types in question as follows:

I. Synchronous motors started by commutation.
II. Synchronous motors started as induction motors.
III. Asynchronous polyphase motors.
IV. Asynchronous monophase motors.

The first two classes have exceedingly valuable properties for certain purposes, but are not suited for railway work requiring very frequent stopping and starting or constant variation of speed.

The third class can meet all requirements as to starting torque and speed variation, and can be made substantially as efficient and durable as continuous current motors, but requires a somewhat troublesome system of working conductors.

The fourth class starts moderately well, is somewhat weak at present in the matter of speed variation, but can be operated on existing systems of working conductors.

I. It is a well known fact that a series wound motor with fields laminated to check eddy currents will start and run fairly well on an alternating circuit, particularly if the frequency is low. The late Mr. Eickemeyer produced a motor of this class which gave admirable starting torque and ran with a good degree of efficiency. The practical difficulty that has hindered the commercial development of such motors is rather severe sparking, which seems to be irremediable and if long continued does serious damage to the commutator.

If, however, the sparking only occurs during the process of starting it is not a difficult matter to avert injury to the commutator, so that if such a motor can be worked normally as a synchronous alternating machine, and as a series commutating motor only at starting, it become capable of doing excellent work.

There are divers other means of starting an alternating motor by means of a commutator. A commutated field in shunt to the armature can be made to give a power of starting sufficient to bring an unloaded motor up to synchronous speed, and in fact, an ordinary compound wound alternator can be made self starting by means of its compounding commutator. These devices do not permit of starting under anything much exceeding friction load and, hence, are inferior for severe work to the series starting device just mentioned and various modifications of the same idea.

II. Synchronous motors of the polyphase type are capable of starting fairly well as induction motors, the field poles serving as armature. When the starting torque is obtained merely from eddy currents in the pole pieces, as in most synchronous motors and rotary converters, the torque is weak and the starting current abnormally large. To secure a quarter of the full load running torque, fully twice the full load current would be ordinarily required, or proportionally less if the motor is starting under merely friction load.

It is quite possible, however, to construct a specialized field with inductive windings in the pole faces, so that the the motor will give its full normal torque at starting on a current not greatly in excess of its full load current, and will be capable of shifting over to synchronous running when up to speed.

In a similar way a monophase motor could be arranged to be self starting as an induction motor and then transformed to the synchronous type.

For starting under load these forms are probably inferior to those starting as series motors by commutation, out they are simpler and sufficient for starting unloaded.

To ordinary street railway service with constant stopping and starting under all sorts of unfavorable conditions, these essentially synchronous motors are inapplicable, since they do not start well enough and are incapable of speed variation when running in synchronism. Nevertheless, they are not to be despised for certain classes of railway work to which we must look forward.

For long lines with stops only at stated stations such motors can even now be made available. If starting by clutch be considered inadvisable there is now no serious difficulty in the way of a commutating start quite good enough to bring a train up to speed. Once in synchronism the motors would drive steadily ahead up grade and down at a uniform speed until the next station was reached. The longer the line and the fewer the stops the better would be the operation of the system.

The great advantage in synchronous motors for such work lies in their freedom from lagging current, and their insensitiveness to changes of voltage. A power factor approaching unity such as can readily be obtained from large synchronous motors reduces the difficulties of transmission very materially, and particularly it diminishes the necessary capacity in the generating station and in the line.

In general transmission plants for a mixed load of lights, synchronous and induction motors, the power factor can be kept fairly high, with careful operation probably up to .85 or .90. This power factor means that for operation at a given voltage ten to fifteen per cent more current must be generated and transmitted than corresponds to the energy delivered. In addition a similar amount of reserve voltage must be available to compensate for the inductive drop in the line and the reaction of the lagging current in the generators.

The total net effect then, of even this power factor is to call for not less than twenty-five per cent extra capacity in the generating plant. Were it not for the fact that polyphase generators have a high output compared with continuous current generators, even this increase would be serious—as it is it is annoying. In plants operating induction motors only, the increased capacity necessary by reason of lagging current may be very much more serious, and makes the synchronous motor a thing not lightly to be put aside as impracticable.

III. Although the asynchronous polyphase motor is now not unfamiliar and its theory is fairly well known to most engineers, its practical characteristics are not widely understood.

We may best regard it as an alternating motor in which the current is led into the armature by induction as in an ordinary transformer instead of by brush contacts. Its field and armature windings are so organized that the currents in them bear to each other the relation necessary to secure effective torque, as in any other motor. Whether the windings which deliver current to the armature are used alternately for this purpose and for establishing a field with which the induced current can react, or whether inducing and field windings are specialized; whether the structure is so disposed that there is a true resultant rotary magnetization or whether there exists a rotary pole only in the sense in which the poles rotate in a continuous current

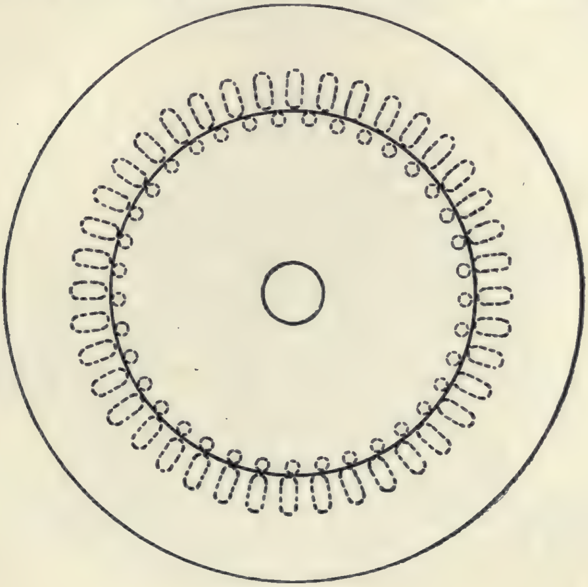


FIG. 93.

armature—all these are questions which have but a trivial bearing on the actual properties of the machines. As a matter of fact induction motors are much closer in principles and properties to continuous current motors than is generally supposed. Like shunt motors they tend to run at a constant speed and when the load changes they speed up or slow down just enough to permit enough armature current to flow to adjust the motor to the new conditions of load. Like shunt motors too, they require at starting a resistance in the armature circuit to keep the starting current within bounds.

Their general properties are very little influenced by the number of phases for which they are wound. There is supposed to be a slight increase of output with increase in the number of phases, but as in the case of multipolar continuous current machines the increased output is more a matter of *finesse* in design than it is dependent on any theoretical considerations.

At the present time all polyphase induction motors are strikingly alike in structural features. With very few exceptions they consist of two concentric annular masses of laminated iron, of which the inner one is supported on the shaft and is free to rotate, while the outer one is carried by the frame of the machine. The outer face of the inner ring and the inner face of the outer ring are provided with slots or holes to receive the windings. Fig. 93 shows the character and relation of these rings. The slots or holes are various in number and shape, but those in the two members are different in number to keep the magnetic relations constant irrespective of the position of the rotating member. The teeth are very seldom developed into anything approaching projecting pole pieces, unless in small motors, as it is desirable to distribute the windings as uniformly as possible. In American motors, the slots are usually open, in European types they are frequently closed as shown.

Both rings are supported in a suitable frame. In one set of slots is wound the primary inducing winding, in the other the secondary or induced current winding. Sometimes one winding rotates, sometimes the other. Conventionally we call the primary member the field and the secondary member the armature.

Fig. 94 shows a fifty horse power, two phase induction motor of a recent design and gives an admirable idea of the way in which such a machine is constructed. In this case the field revolves, while the armature is stationary. The working current is led into the field through the three collecting rings just outside the bearing, the two phases being given a lead in common at the motor. This revolving field construction has several well marked advantages. The primary element in which the heaviest hysteretic loss occurs is reduced to the smallest practicable dimensions. The secondary being stationary can have resistance put in series with it through ordinary binding posts, sometimes a great convenience, and since the secondary winding is, as shown, very simple, the armature can be split like the field of a dynamo and the upper half lifted off to permit inspection or removal of the revolving field. As the clearance in in-

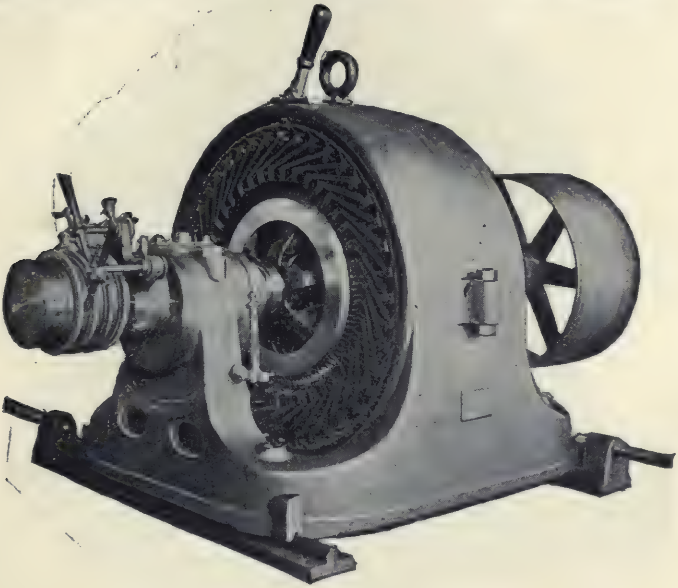


FIG. 94.

duction motors is usually very small, ⅛ in. or less, such an arrangement is very convenient.

Fig. 95 shows a fine three phase motor of 125 h. p., in which the armature revolves while the field is stationary. The main leads are taken to the connection board on the top of the motor, and there are no moving contacts whatever. The resistance used in starting the motor is stowed inside the armature ring and its terminals brought out to three contacts secured to the armature spider. When the motor is up to speed these are short circuited by a solid ring slipped a couple of inches along the shaft by the small handle shown alongside the bearing. Sometimes this resistance is in two or more sections, successively short circuited by a similar motion of the ring. This arrangement does away once for all with all moving contacts. The field, being stationary, can be safely wound for higher voltages than if it were rotating and suffers less mechani-

FIG. 95.

cal strain at all voltages. The machine thus requires very little attention, and besides is quite free from all danger of sparking, sometimes a very undesirable possibility.

Both the constructions shown have merits for special purposes. The revolving armature arrangement gives a simpler and safer machine for most ordinary purposes, and especially for high voltage work without transformers. The revolving field is the better for very large motors and for all work requiring considerable and variable resistance in the armature circuit. It is therefore, particularly well adapted for railway work at varying speed, hoisting and similar severe service. In general properties, efficiency, power factor, regulation and so forth the two constructions are indistinguishable.

For effectively meeting the demands of railway service a motor must be simple, durable and easy to inspect and repair; it must also be capable of regulation in speed within rather wide limits, must have great initial torque, and must have a good efficiency. The first three mechanical qualifications the induction motor is amply able to meet.

The simplicity of the structure has already been set forth. The nature of the field winding is well shown in Fig. 96, the field of a slow speed, two phase motor of one hundred horse power output, and the winding is for 2000 volts. In ordinary American practice the field coils are in open slots so that they can be the more readily repaired or replaced. The armature winding is usually of massive bars with heavy end connections and is well exhibited in Fig. 94. The matter of durability is best settled by experience. During the past seven years there have been put in operation in this country polyphase induction motors aggregating more than 50,000 h. p. in output; and from the author's own personal knowledge it may be said that the repairs upon these have been almost negligible, far smaller than in any other class of moving electrical machinery. This is a strong statement, but it is fully borne out by the facts.

Speed regulation in polyphase induction motors is effected by means not unlike those used for continuous current motors. A common shunt motor may have its speed varied in two very simple ways. First, the field strength may be changed; second, the armature current may be cut down by a rheostat. A series wound motor may be similarly governed by changing the field strength or changing the voltage.

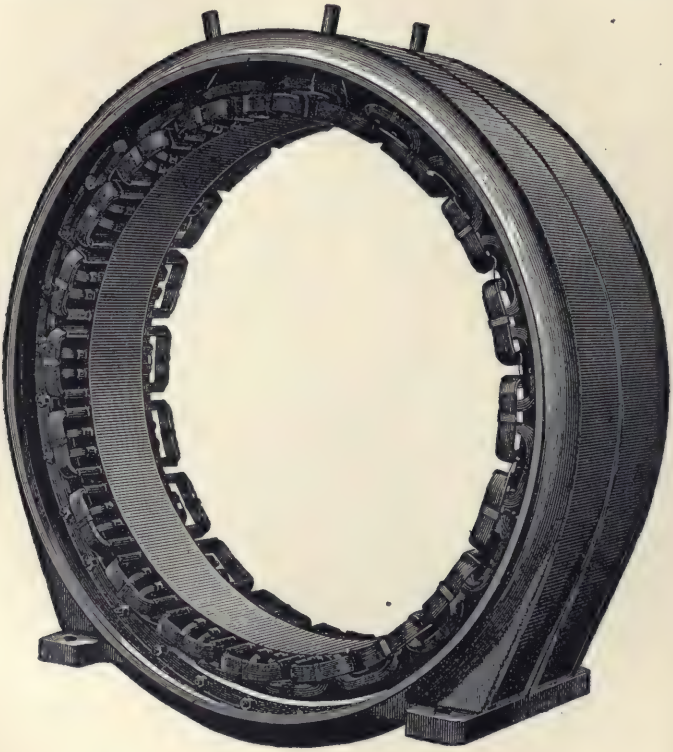


FIG. 96.

In an induction motor the same devices are used in a somewhat different way. Weakening the field of such a motor by reducing the voltage of supply causes the armature to run slower, but since the armature current is supplied by the field as a transformer the armature is also greatly weakened and, hence, the torque falls off very rapidly as the voltage is lowered. Modifying the armature strength by a rheostat in circuit, however, cuts down the speed until the added transformer effect of the field supplies current enough to handle the load at the new rate of speed. By varying the resistance in the armature circuit the speed can be varied to any desired extent, the torque remaining constant throughout. Fig. 97 shows the speed variation characteristics of a fifteen horse power induction motor with a rheostat in the armature circuit. Starting at full output and speed, the speed was gradually lowered from 1400 r. p. m. to 150 r. p. m. The torque remained uniform, so that the output was almost exactly proportionate to the speed. The relation between them is shown in curve A. The input meanwhile remained nearly constant. B gives the variation of the power factor and C shows the slight and gradual diminution of the input.

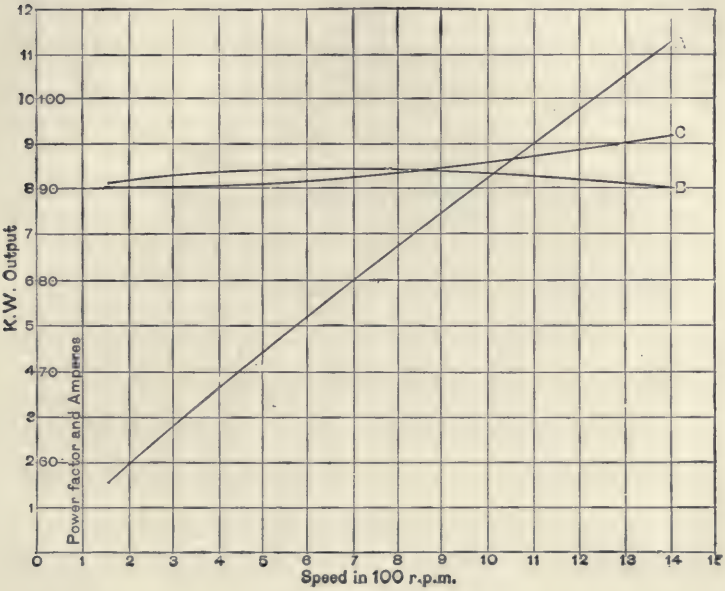
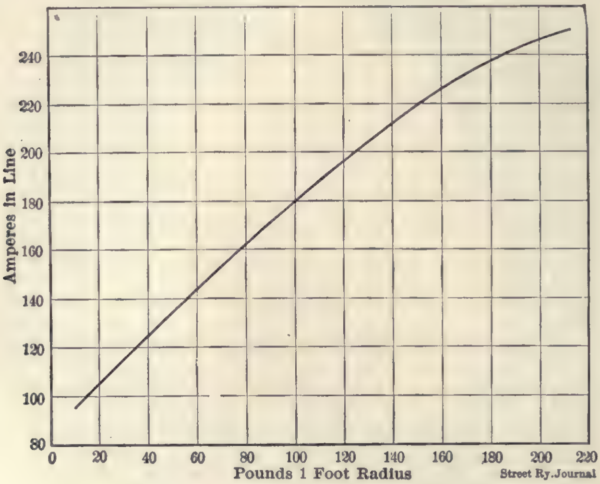


FIG. 97.

Altogether this motor behaved almost exactly like an ordinary railway motor with rheostatic control, regulating quite as well and with closely similar inefficiency.

At full load this motor had about the efficiency of a fifteen horse power motor of the ordinary kind, but substantially all the reduction in output by lowering the speed represented loss of efficiency as is the case with a series wound, continuous current railway motor with rheostatic control. The power factor in this case was notably high at all speeds, high enough to cut very little figure in the operation of the system.

A car equipped with motors like the one under consideration would handle very easily as regards speed variation and would give quite as good efficiency as hundreds of cars now in operation. For interurban and similar work in which running at reduced speed is the exception, the efficiency would be all that can reasonably be desired.



Street Ry.Journal

FIG. 98.

As regards starting torque, which for railway motors is a consideration of prime importance, the modern two or three phase motor leaves little to be desired. Not only will it start with very great torque, but it will give this torque with relatively less current than will a series continuous current motor. That such must be the case is obvious from the fact that while the fields of an ordinary railway motor are nearly saturated at all working loads, the fields of an induction motor are normally worked at low saturation to avoid hysteretic loss, so that since the torque of a motor is proportional to the product of armature current and field strength, doubling the input in an induction motor nearly quadruples the torque. This is well shown in Fig. 98, which gives the relation between current and starting torque in the motor referred to in Fig. 97. The maximum torque was obtained with a very small resistance in the armature circuit, which resistance was gradually raised to obtain the other points in the curve. The torque was truly static and the power factor of the machine under this condition was lower than when running normally, as shown by the larger current than in Fig. 97.

The maximum starting torque, more than four times the full load running torque, was obtained at normal voltage by the use of about 2½ times the normal full load current.

Four times the normal drawbar pull is enough for ordinary starting purposes even in severe street railway service, but even this can be still further increased if necessary, by raising the voltage. The torque, so long as the field is unsaturated, then increases nearly in proportion to the square of the applied voltage. Thus, if the field coils of the motor are in the star connection for normal operation, and are thrown over to the mesh connection as an extreme measure, the applied E. M. F. per coil is increased in the ratio of 1.73:1, and the resulting torque is three times the normal. This in combination with the changes of armature resistance indicated in Fig. 98, is enough to increase the torque enormously in spite of increasing saturation of the field. In fact one can obtain from an induction motor more starting torque than is ever called for in practical work.

Fig. 99 shows the results obtained in testing a pair of three phase induction motors specially arranged for railway work. Each motor was designed to produce a normal drawbar pull of 800 lbs., equivalent at full car speed to about twenty-five horse-power. These machines were wound for 110 volts between lines, weighed substantially the same as standard railway motors of the same output and were coupled up to a special controller, designed to vary both the armature resistances and the field connections. These connections were threefold, the mesh or △ for extreme torque, star or Y for normal full speed running, and "concatenated" for half speeds. The latter was a quasi-series connection giving much the same result as reducing the primary voltage, without calling for special appliances. It consisted, practically, of using the secondary current of one motor as the primary current of the other, and of course suffered through adding the inductances of the two.

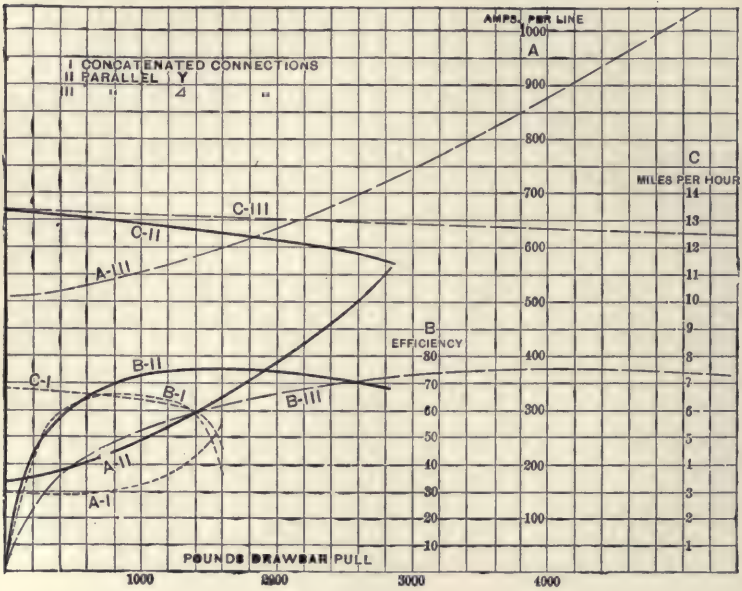


FIG. 99.

The A curves refer to current, the B curves to efficiency, and the C curves to speed of car. Although the concatenated connection was decidedly inferior in efficiency, both real and apparent, to the others, it still gave half speed very smoothly and with an efficiency reasonably high. The drawbar pulls registered were amply great for any service conditions, and the net commercial efficiency given, which includes all the gearing losses, compares not unfavorably with ordinary continuous currents. The running of the motors was as good as could be desired, and the abolition of the commutator is a very material gain, since collecting rings give decidedly less trouble. Change of armature resistance gave opportunity to pass smoothly from one field connection to another without jerking the car. As appears from curves C II and C III, apparatus of this kind has the very considerable advantage of fairly constant speed over a wide range of drawbar pull. Although polyphase induction motors are termed asynchronous they have so strong a tendency to run near synchronous speed that they have the power of driving ahead regardless of grades unless grossly overloaded.

None of the methods of regulation as yet devised is quite the equivalent of the series parallel control so extensively used in continuous current practice, so far as efficiency is concerned. It is possible to get, however, as complete control of the speed and nearly as good efficiency at all except the lowest speeds. In the line of work for which alternating motors are most needed, i.e., long interurban and similar lines the need of highly efficient control at very low speeds is not so great as in ordinary street railway work, since by far the largest aggregate output is at the higher speeds.

In spite of the extent to which induction motors have been used in the past seven years, no important apparatus is less generally understood. Even engineers who are well posted in other matters are apt to be dismally ignorant of the practical properties of induction motors. They have too often derived their scant information from scholastic papers on the subject full of solemn inanities on the general theory of rotating magnetic poles, fortified by eminently respectable equations which are valuable only to those who know the limiting conditions.

In point of fact the induction motor is a most simple and reliable machine much closer in its properties to continuous current motors than is generally supposed.

Its adaptation to railway work is beset with fewer difficulties than confronted the continuous current motor a dozen years ago. The nature of those arising from speed regulation we have just considered. The state of the case is about as follows: Wherever rheostatic control of railway motors is sufficient, the use of induction motors presents no special difficulty, giving the same power of speed regulation upon the same terms as in continuous current practice. This clears the way at once for much long distance and interurban work. In urban and suburban work upon a large scale something more is necessary. Several methods are available, as has already been indicated, concatenation and the passage from mesh to star connections being the most advantageous yet tried. The application of these methods is now in the tentative stage, with the chances good for a favorable result when the work is seriously attempted. It should not be forgotten that series-parallel control of regular railway motors was tried and abandoned on account of forbidding complications several years before it was taken up again and pushed through to definite success.

Another interesting suggestion for speed variation is varying the number of motor poles. As an induction motor has no salient poles this is a possible procedure, but it does not promise very good properties at the lower speeds at ordinary frequencies. Varying the impressed E. M. F. by reactance in the primary circuit suggests itself as the simplest method of control. Practically, however, it leads to lower efficiency at all speeds than the rheostatic control and at low speed the power factor is infamously bad. All these things will have to be threshed out experimentally as the present railway apparatus has been.

The question of actual armature speed deserves consideration in this conection. As a starting point it will be convenient to remember that in ordinary practice one mile per hour means very nearly ten wheel revolutions per minute. The usual gear reductions found in standard railway motors range from about 1:4.8 to 1:3.5. Hence for a normal speed of 10 miles per hour, one may say roughly that the armature speed should be not over 500 r. p. m. and would not probably be below 400 r. p. m. An 8 pole motor at 30 ∿ would give at load say 425 r. p. m., hence at speeds below 10 miles per hour some form of controller would have to be used. This is somewhat awkward for urban work, although it does not differ materially from everyday street railway practice. It simply means the same sort of inefficiency at low speeds to which we have long been accustomed. There is this difference, however, that the polyphase motor could not at that frequency run above 10 miles per hour, which would be a bit awkward in suburban running. Probably a frequency of 40 ∿ would prove a convenient compromise, or a 6 pole motor at the lower frequency. The conditions just mentioned are compatible with a thoroughly good motor in other respects. The peripheral speed of the armature would probably be somewhat higher than is usual in continuous current railway motors rising to 2500 feet per minute as against 2000 or thereabouts for a common railway motor under similar conditions. In fast suburban work these speeds might be doubled. There is no possible objection to such surface velocities for either kind of motor.

An utterly foolish opinion is just now abroad that induction motors demand enormous peripheral speeds, which is not at all the case, as the above will show. When worked at 60 r. or more it is convenient to run the armatures at a surface velocity of 5000 feet or so, but at low frequency it is quite unnecessary.

For interurban work one would probably choose a 4 pole design, giving say, 850 r. p. m. of the armature at 30 ∿, with a full speed of about 20 miles per hour. The power to pass from 8 to 4 poles or the reverse would obviously be very convenient, but the electric railway was an established success on a large scale long before any better means of regulation than the rheostat was in use. It is perfectly feasible then to work three-phase motors in a precisely similar way for interurban or even urban work, when conditions make it desirable.

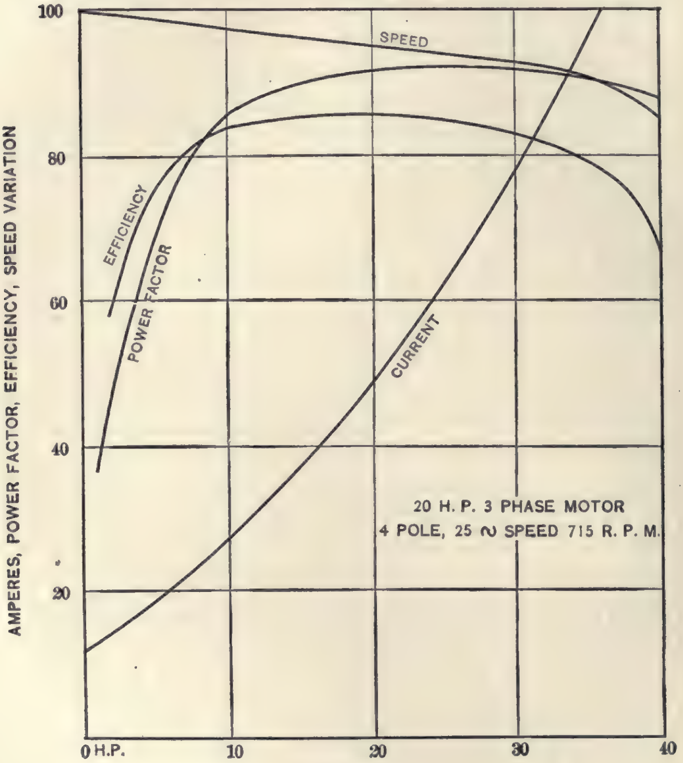


FIG. 100.

We have already discussed the properties of such motors somewhat, but a further examination of the attainable qualities in a practical motor for street railway service may be worth the while. A good idea of the performance of a well designed three-phase induction motor of about the size and speed required for railway work is given in Fig. 100.

The curves are from a 4 pole, 25 ∿ machine having a normal rating of 20 h. p. and capable of working up to double that power. The full load speed is 715 r. p. m.

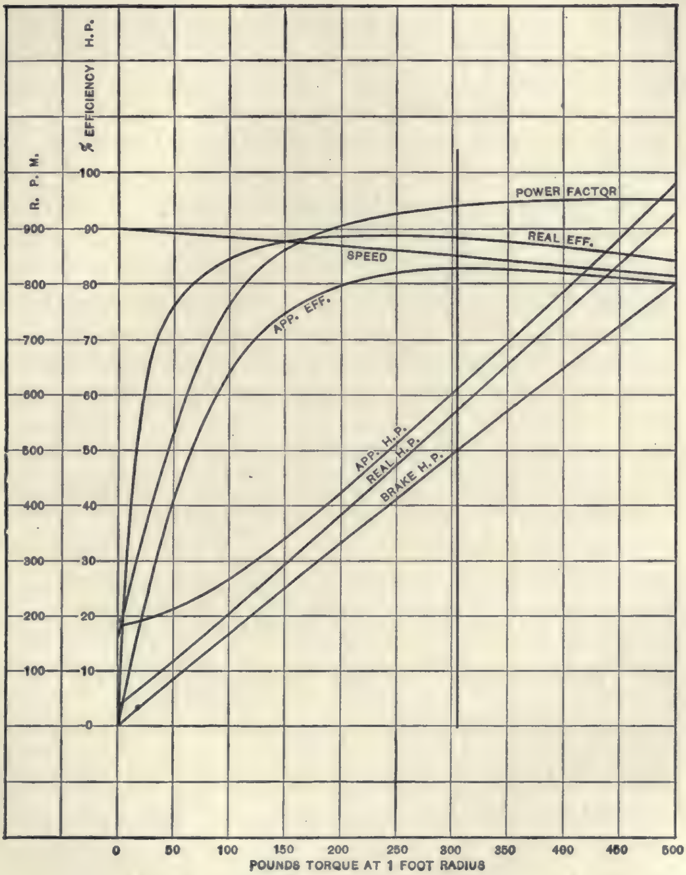


FIG. 101.

which corresponds to a car speed of about 15 miles per hour. The current (at 220 volts) for full load is 49.7 amperes, and for 40 h. p., 130 amperes, while the current running light is 13.55 amperes, the input in watts being

960. The power factor and commercial efficiency are high all along the line, the former passing 80 per cent at about ⅓ load, rising to 92 at a little above full load and holding up to 88 even at double output. The latter stays above 80 per cent from 6 h. p. to 34 h. p. rising to 86 near full load. This motor heated but little, the field conductors rising but 40°C, and the armature conductors only 22°C after a full load running test of 3 h. 30 m.

Results even better than these can be attained, as is shown in Fig. 101. This is from an 8 pole 60 ∿ motor of 50 h. p., having a full load speed of 850 r. p. m. This latter motor, however, is operated with a very small armature clearance, while the former had a clearance of about $\frac{3}{32}$ in. For railway work a little greater clearance would be desirable, about ⅛ in. The effect of this would be to lower the full load power factor to about 90 per cent in each case, with no material change in the efficiency. The long and short of the matter is that by careful design it is perfectly feasible to produce an induction motor having an efficiency as good as that of the usual railway motor, and a power factor good enough to dispose forever of the bugaboo of "false current," as a practical factor in the situation. The motor of Fig. 100 fitted for railway use with gears and gear casings weighs about 2000 lbs. at an outside estimate, which is not at all bad for a motor of that capacity. One must remember that while some street car motors would show considerably less weight per horse power than this, they are, as a rule allowed pretty stiff heating at their rated load, and as a class have been industriously skinned in the matter of weight for the last ten years. Street railway motors, less gears and cases, usually run from 50 to 70 lbs. per h. p. according to rating, while standard induction motors for stationary service weigh on an average from 65 to 70 lbs. per horse power, sometimes down to 60 lbs. or less.

The effect of rheostatic speed regulation on the efficiency of induction motors is worth a brief examination. As regards power factor, Fig. 97 gives the facts in the case, showing that on the lower speeds the power factor is quite as good as at full speed and load. The efficiency as already stated falls with the speed, in fact almost directly as the speed. The motor of Fig. 100, giving a maximum efficiency of 86 should show about 43 per cent at half speed and 22 per cent at quarter speed.

These facts are set forth not for the purpose of recommending induction motors for indiscriminate use on electric railways, but to point out that induction motors are to-day better developed for such work than were the continuous current railway motors that built up the railway business eight or ten years ago. It is not too much to say that at the present time it is practicable to build polyphase induction motors quite good enough for the entirely succesful operation of the long interurban lines for which they are most needed, and that their use would secure certain advantages not otherwise to be obtained, in the economical distribution of power.

The weak points of polyphase induction motors for railway work are as follows:

I. Necessity for at least two trolley wires.

II. Lagging current.

Inasmuch as all true polyphase systems require at least three working conductors, the best that can be done in supplying polyphase current is to utilize the rails for one conductor and provide separate trolley wires for the other two. In rare instances it might be possible to use a third rail and a single trolley wire or even to utilize the two track rails as separate conductors, but such cases are likely always to be exceptional. In conduit work, of course, two working conductors are available without much difficulty, but for general purposes the burden of two trolleys is difficult to avoid.

Most street railway men strongly dislike the double trolley in any form, and beyond question it complicates the overhead work, where crossings and turnouts are frequent, in the most frightful manner. Nevertheless even for city work it can be made steadily operative, as the experience of some years in Cincinnati has shown. The principal advantages of the continuous current, double trolley system which are its only excuse for existence, viz., the independence of track condition as regards motive power, lessened interference with other circuits, and absence of electrolysis, do not apply with the same force to a double trolley polyphase system. One branch of the circuit is still grounded and bad track contact is bound to be felt in the operation of the motors under some conditions. In short the double trolley for polyphase work is a disagreeable necessity and nothing better.

Again, however, comes to the rescue the fortunate circumstance that in much of the long distance work for which alternating motors are desirable a double trolley wire is less objectionable than elsewhere.

The matter of lagging current is more serious. Were all induction motors possessed of as good power factors as the one shown in Fig. 97 there would be no trouble, for the lagging current is too small to influence much either the capacity of the plant or its regulation. But armature clearance is a potent factor in varying the power factor, and the motor in question being intended for hoisting had a clearance but little over $\frac{1}{16}$ in. This is too small for the rough and tumble work of electric railroading, and with double this clearance, as in case of the motors of Fig. 99, the power factor is not nearly so favorable. A good power factor of .85 to .90 is very hard to obtain in motors of moderate size and speed such as would be used in street railway practice, and a poor power factor means mischief.

Take for example a power factor of .75. This means that a third more current must be generated and distributed than is indicated by the energy and the voltage of supply. Hence the saving in copper effected by the three phase or two phase three-wire circuits is more than wiped out at once. Moreover, the large inductance of such a circuit involves both a heavy inductive drop and a very unfavorable armature reaction in the generator. Between these and the extra current the station capacity required would not be less than 1½ times that needed to supply the same effective energy by continuous current.

With large induction motors intended for rather high

FIG. 102.

speed it is practicable to keep the power factor well up, high enough to render this trouble quite insignificant.

All these facts point to the desirability of developing polyphase work in the direction of fast interurban service and heavy long distance work rather than toward ordinary street railway equipment. In the former the polyphase system is at its best, its many good features are thoroughly available and its disadvantages are minimized.

Nevertheless the abolition of the commutator is so desirable that there is a strong tendency to work polyphase apparatus for ordinary purposes, and it is noteworthy that the first polyphase electric road to be put in operation belongs distinctively to the class of street railways. This very important piece of pioneering work was carried out in 1896 by the famous firm of Brown, Boveri & Company, at Lugano, Italy.

Lugano is a fine prosperous town situated on the lake of the same name at the foot of the Italian Alps. A waterfall a little more than seven miles away furnishes power for lighting the town, and is now utilized for the railway as well. The road runs for the most part along the lake front on each side of the town. It has a total length of almost exactly three miles, and its general situation is shown on the sketch map (Fig. 102). There are only moderate grades of about three per cent except for three short pitches of six per cent.

At the power station is a 300 h. p., horizontal turbine direct connected by a flexible coupling to a 150 k. w., three phase generator. This machine is of the inductor stationary armature type generally advantageous for high voltages and is wound to give directly 5000 volts between lines at 40 ~. The exciter armature is carried directly on the main shaft so that the generator is quite self contained. Its speed is 600 r. p. m.

The line is of three wires each about No. 4 B. & S. gauge, and leads at present to a single transformer station on the southern edge of the town not far from the middle of the line. The three phase transformer here located reduces the voltage to 400 volts which is the working pressure between the conductors.

The conducting system consists of the track which is thoroughly bonded, as one lead, and two trolley wires, each about No. 3 B. & S. gauge. Bracket construction is employed and the two trolley wires are carried side by side about ten inches apart. The general character of the overhead structure is well shown in Fig. 103. The current is taken off as there shown by two distinct trolley poles set one behind the other about forty inches apart. This separation of the trolleys, by the way, has been found to be the best arrangement when using a double trolley continuous current system. The trolleys themselves are very similar to those generally used in this country.

FIG. 103.

Four motor cars are now in use, each of them having a twenty horse power induction motor geared, with a speed reduction of 1 to 4 to one of the axles. The arrangement of the motor and its suspension from the truck is shown in Fig. 104. The motor itself (Fig. 105) is of the iron clad type with revolving armature furnished with three collecting rings. These rings permit the insertion of a three-part resistance in the secondary circuit for the purpose of speed regulation. The function and practical effect of such a rheostat has already been described. In this case it has been found to permit perfect control of the speed, as might be anticipated, but with poor efficiency at low speeds. The normal car speed is between nine and ten miles per hour. The starting torque of the motors has proved to be ample, quite sufficient to start a very heavily loaded car from rest on the steepest grade on the line, and the performance of the cars has been on the whole very good. The two trolleys perform well, and, what is rather extraordinary, the heavy alternating currents have not given so much trouble as might be expected to the telephone system of the town. There must be a strong element of good luck in this matter, for under ordinary circumstances induction would be at least quite perceptible, although the leakage difficulties, of course, are practically suppressed as are also most electrolytic troubles.

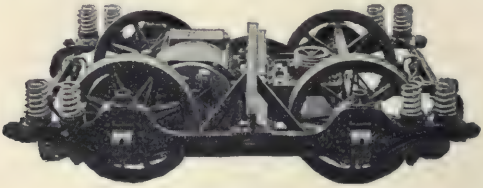


FIG. 104.

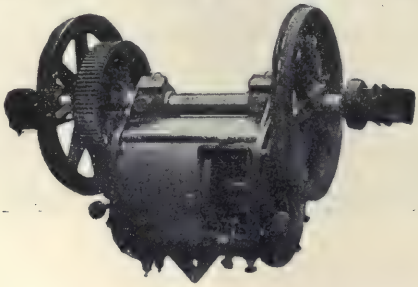


FIG. 105.

In some recent two-motor car equipments made by Brown, Boveri & Company, a quasi-series connection has been employed for low speeds, the induced current from one motor serving as the inducing current in the other as in the "concatenated" arrangement already mentioned. Although such devices are, as indicated already, useful in giving a fair efficiency at low speeds, they can hardly be regarded as the full equivalent of the series parallel controller now so generally and successfully used with continuous current motors.

Last July a notable example of three-phase railway work was put into operation by the same enterprising firm. This is a true interurban road 25 miles long between the towns of Burgdorf and Thun, Switzerland, running through several smaller towns on the way and connecting at each end with a steam line. The power station is on the Kander River at Spies, about 6 miles beyond Thun and the end of the railway. Here are installed three phase generators direct coupled to turbines. From the raising transformers current is delivered at 16,000 volts, 30 ∾, to the railway transmission line. This line consists of three 5 m. m. (about No. 4 B. & S.) bare wires supported on porcelain insulators. The line follows the road in general, with occasional short cuts across curves, and

FIG. 106.

feeds 14 transformer stations which reduce the pressure to 750 volts for the working conductors.

These latter are of 8 m. m. (about No. 0 B. & S.) wire carried on cross suspensions, the two conductors being about 43 ins. apart and about 16 ft. above the track.

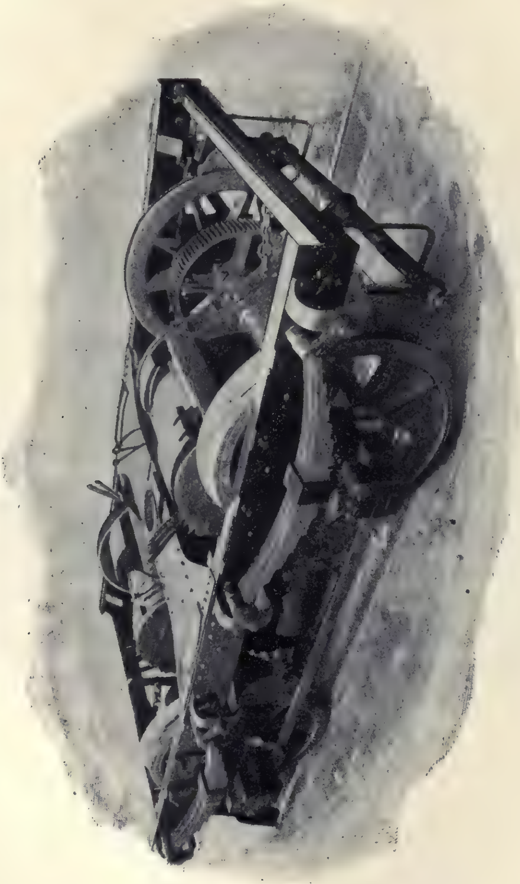
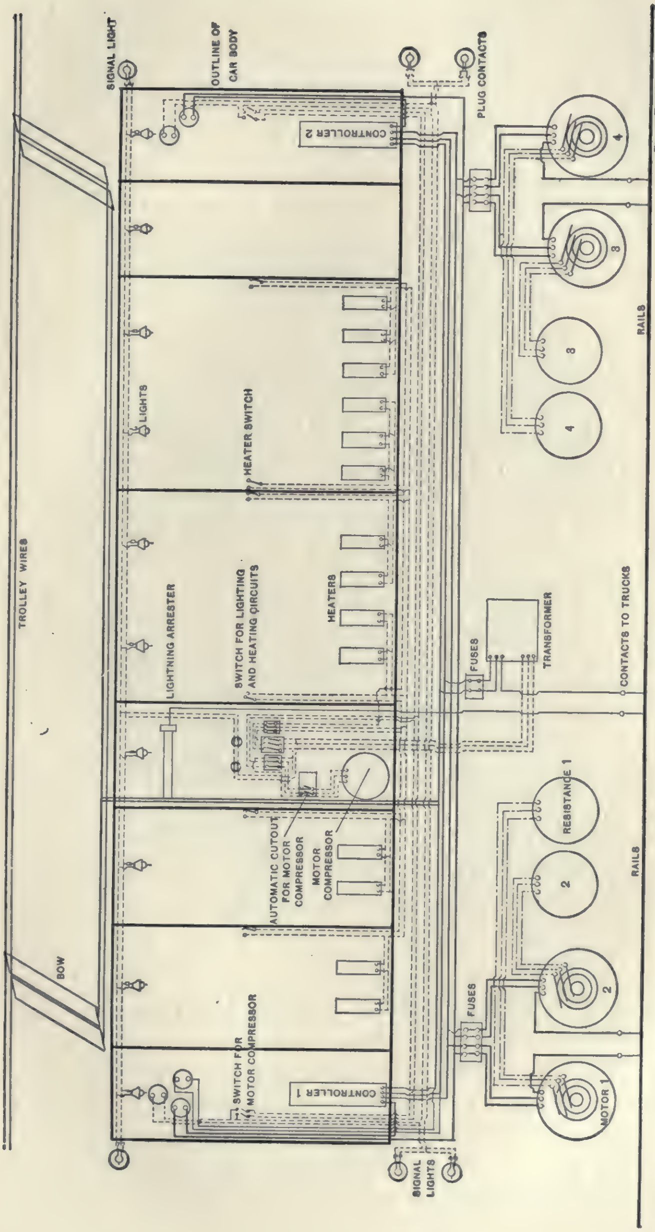


FIG. 107.

The road is single track with turnouts, of 5 ft. gauge, and is laid with a plain T rail weighing about 73 lbs. per yard, on steel ties placed a little over 30 ins. between centers. The maximum grade is 2.5 per cent.



Street Railway Journal

FIG. 108.

The electrical equipment of the road consists of two locomotives, each driven by two 150 h. p. motors, and six motor cars each with four 55 h. p. motors. Current is taken from the working conductors by four bow trolleys in pairs side by side at each end of the car. Fig. 106 gives a good idea of the motor car, trolleys and working conductors. The motors are arranged much as is usual in four motor car equipments, two on each truck, single geared to the axles. Their full load speed is 586 r. p. m. and they are controlled by rheostatic resistances in the revolving secondaries. Fig. 107 shows the general arrangement of the trucks. The wheels are 40 ins. in diameter corresponding to railway rather than tramway conditions. In fact the whole line is worked on the block system and follows railway practice throughout, the cars being equipped with air brakes and run in short trains as in ordinary suburban work, at a normal full speed of 22.5 m. p. h. The brakes are worked by an automatic motor compressor and the cars are lighted and heated electrically. In general the whole equipment is that of a thoroughly up-to-date heavy interurban electric road, developed for polyphase transmission. Fig. 108 gives the electrical diagram of one of the motor cars showing the various connections. It should be noted that the rheostats are worked by a rod from the controller instead of being electrically connected to it. The motor cars accommodate 68 passengers and weigh fully equipped 32 tons. The locomotives are intended largely for freight service and have a capacity sufficient to haul easily a 100 ton train up the 2.5 per cent grade at a little better than 11 m. p. h. They have, however, change gearing to enable them to be speeded up for passenger traffic when needful.

Fig. 109 shows one of the fourteen transformer stations. Each of these consists of a 450 k. w. three-phase oil transformer in a sort of gigantic metallic sentry box on a concrete foundation. Above and in the rear are the cut-outs, fuse boxes and lightning arresters. The transformer stations are located close to the way stations, and are under the charge of the station masters. The whole system is a practical demonstation of the applicability of the three-phase system to the working of interurban lines on a large scale. The most startling thing about the road is the singularly small amount of copper required. Aside from the high tension line there is no feeding system, all the current being distributed over the working conductors. The total copper in the system is only about 145,000 lbs. worth at the basic price of 15 cts., $21,750, less than $1000 per mile of line. This for a system designed for motors of more than 1800 h. p. total capacity is sufficiently remarkable to afford considerable food for contemplation. American engineers have fought shy of undertaking this line of work, preferring the easier but more costly and

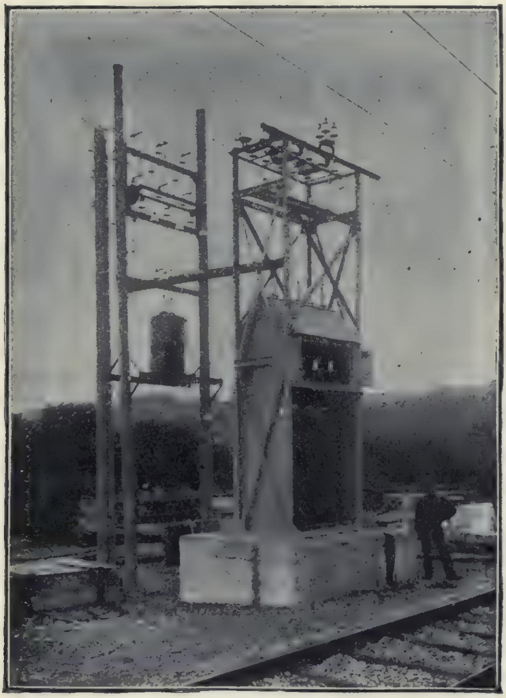


FIG. 109.

less efficient method of transmitting to rotary converters. In the logical development of railway work, however, the polyphase motor certainly has a legitimate place and it is unwise to make a fetish of uniformity to the extent of barring the way to progress.

The problem is being worked out for us abroad in roads like the one just described, and in due time we may profit by it as we profited nearly a decade ago by the Lauffen-Frankfort experiment in polyphase transmission.

IV. Motors of the asynchronous type working on a monophase circuit are not as yet far enough developed to be immediately available for railway purposes, although they have come abroad into considerable use for general motor work in connection with lighting service.

They may be divided into two classes, rather distinct from each other in method of operation, although closely similar to each other in principle and in practical qualities.

First may be mentioned those motors which are operated as true polyphase motors by derived polyphase currents obtained by splitting up a monophase current. In this case the actual motor is a true polyphase machine with all the properties thereto belonging, and the real novelty of the system lies in the special methods of transformation adopted in breaking up an ordinary alternating current into symmetrical components.

Systems of this sort have been brought forward in this country by C. S. Bradley and abroad by M. Désiré Korda. They are somewhat complicated, but are nevertheless operative, and may find a field even in electric traction, particularly in special problems in railroading.

The apparatus of Mr. Bradley is shown in diagram in Fig. 110. The process employed consists essentially of two operations—the splitting up of the original current into two components, differing in phase by 90 degs., and, second, the combination of these to obtain a three phase resultant system. In the diagram, A is the generator, B one section of the transformer primary system, D a condenser which acts in conjunction with the inductance of the compound section of the transformer system to produce the requisite 90 deg. phase difference, *n* and *l*, the parts of the compound transformer, and *g h i j k* the segments of the secondary windings. Once given the two phase current, the shifting over to three phase is easy. The coil, *i*, furnishes one phase, the resultant of *g* and *k* a second, and the resultant of *h* and *j* the third, all of which are connected in the ordinary way to the motor, M. The result of this very ingenious combination is a very close approximation to a true three phase relation throughout a considerable range of load, both in starting and running. The use of three resultant phases tends to preserve a more uniform phase relation than would be obtained by utilizing the original two derived phases.

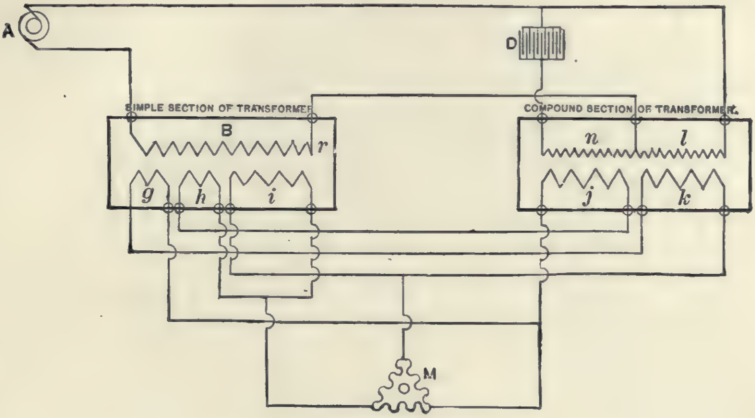


FIG. 110.

The employment of a condenser, while it adds to the complication, tends to annul the inductance of the main circuit. At all events it can be made to give a very high power factor, better than that given by ordinary polyphase motors.

On the other hand, the condenser is an element of weakness in that it is of somewhat uncertain life, and unless exposed to high voltage and used at rather high frequency, is both bulky and expensive. Its use involves difficulties in the way of maintenance that, while probably surmountable, are serious in its application to railway conditions.

M. Korda's device dispenses with the condenser and initially splits up the primary monophase current into two components 60 degs. apart by inductance alone and recombines these so as to give three phase resultants. It gives a somewhat less stable phase relation and power factor than the method just described employing a condenser.

Second in the list of motors for monophase circuits comes that class which employs a split phase current at starting to obtain a simultaneous transformer and motor action, but in running is purely monophase. Motors of this kind have been considerably developed abroad, but are only used tentatively in this country. As at present made they all start either with very poor torque, or if with better torque demand an enormous starting current, which lags badly. When once up to speed, however, they perform well although never with as high output as a polyphase motor of the same dimensions and efficiency. There are a large number of ways of getting the phase difference at starting, some of them requiring modifications of the motor structure, others merely special connections. A considerable variety of phase splitting devices were devised by Tesla as corollaries to his pioneer polyphase work and divers others have been added to the list. Variations of capacity and inductance in branches of the main circuit external to the motor are most often used.

In construction and appearance these monophase motors are closely similar to the polyphase ones already described. Indeed most polyphase motors can be worked as monophase motors with very trifling changes. When carefully designed, these machines give a high efficiency and a high power factor when once at speed. Fig. 111 gives the curves of efficiency and power factor for a fifteen horse power, Brown, monophase, asynchronous motor designed for a speed of about 850 r. p. m. at 40~.

These results are nearly as good as can be obtained from a polyphase motor of similar output, but since most of these monophase motors are built with exceedingly small clearance for the armature, down to less than $\frac{1}{32}$ in., there is little likelihood of approximating closely the figures just given with a motor fit for railway work. Nor is it possible to get effective speed regulation in monophase motors by a resistance in the secondary or any other simple means.

Summing up the present state of the art, we find that the only alternating motors yet constructed, of properties immediately suitable for railway service, are the polyphase induction motors, which while often weak in power factor, are of sufficient efficiency and general excellence to replace existing continuous current motors. It is certain too, that the lag factor trouble can be overcome by careful design particularly if the frequency is kept low, say, 30∼ to 40∼.

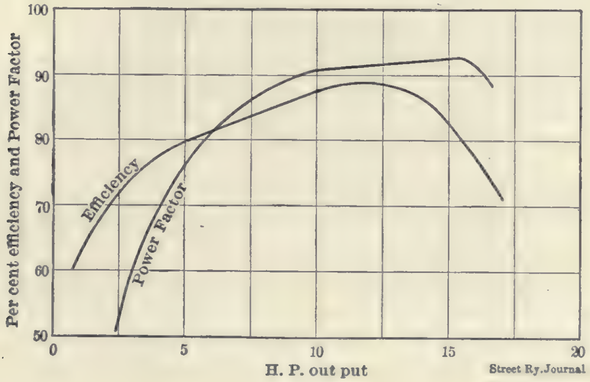


FIG. III.

The synchronous motors, both monophase and polyphase, have excellent properties when up to speed, but do not start will except at the cost of considerable complication. The commutating start appears to give the best torque, but this is not comparable with the best that can be done by polyphase induction motors. The whole class are liable to poor power factors when starting, though when running the power factors are uniformly high.

The induction motors for monophase circuits are still in an early stage of development as regards application to such severe service as is necessary on electric railways. The most promising of them are those supplied with derived polyphase currents even if this advantage involves the use of condensers, since they can be made to give high starting torque and a good power factor. The starting devices applied to all existing strictly monophase motors are entirely insufficient for railway purposes unless a clutch connection is used in which rather unmechanical case synchronous motors would be generally preferable.

With derived polyphase circuits, at least for starting, it is, in the author's opinion, entirely practicable to produce even now a motor for monophase circuits entirely capable of doing certain railway work successfully.

It does not follow from this that all classes of electric railway work can now, or ever, be accomplished best by the use of alternating motors of any sort. But the same logic of circumstances that has brought alternating systems into increasing use for lighting and general power purposes applies to railway work with ominous force. It is altogether probable that for a vast amount of strictly street railway work the continuous current motor is here to stay. In its present state of development it is, at least as a motor, as good as any alternating current motor is likely to be. But the question of voltage presses hard, and as the distances to be reached continually grow the time comes when a distribution that can be used for continuous current motors becomes outrageously costly in material or in loss of energy. The economic value of alternating motors depends on their adaptation to a very economical method of distribution. In many cases they not only meet this condition, but can be applied with advantage irrespective of the distribution system.

For urban work they possess few intrinsic advantages over continuous current motors. For much interurban and long distance work they are not only important as a part of the distribution, but have some material points of superiority. In such work, with infrequent stops at stated intervals, their tendency to run at a uniform speed irrespective of grade and load must be very useful in maintaining the running schedule. The maintenance of speed in spite of moderate variations in voltage is also useful in working long feeders at variable load, and the possibility of working at high voltages greatly simplifies the problem of drawing large amounts of energy from the working conductors.

The alternating motor is then fortunately best adapted to that class of work in which the exigencies of distribution make it most necessary. In high speed and long distance work lies its chief strength, and when this kind of railroading is attempted in earnest it is quite safe to say that alternating motors will be used.

For light railways running considerable distances across country also, the alternating motor is peculiarly adapted.

In no way can the importance of this branch of work be exhibited more forcibly than by computing the initial and operating expense of a road under assumed conditions; first, utilizing continuous currents; second, employing transmission to substations with rotary transformers, and finally, using an alternating distribution with alternating motors. It is, of course, quite impossible to select a case that will be exactly equally fair to all three methods, but we can, perhaps, approximate to a fair general case.

Let us assume an electric road thirty miles in length running through a series of villages with two cities of moderate size as termini. For simplicity we will assume that the cost of fuel and labor is uniform throughout the line so that the location of the station is uninfluenced to any extent by local conditions. The train service we will assume to be conducted on a twenty minute headway, the actual running time being two hours, including stops. This would keep twelve cars in service. We will also assume the grades to be moderate so that the power required would be fairly uniform throughout the line. The cars stop at fixed points only, with good opportunity for clear running over a large part of the system. With ordinary conditions of load the use of two twenty-five horse power or thirty horse power motors per car would be sufficient and the normal current demanded should not exceed fifty amperes per car or one hundred amperes per car, at 500 volts as a maximum for the system. The total output to be delivered tc the cars may then be taken at 300 k. w. average and 600 k. w. maximum.

For such a line as this four methods of supply would be worth investigation: I, direct supply from two symmetrically placed stations; II, supply from a single station with boosters; III, supply from one station with a rotary transformer substation; IV, supply from a single station by alternating currents and static transformers. For simplicity, we will assume the cost of track and overhead structure to be the same for all four. So, in fact, it would be for the first three methods, and the extra working voltage readily obtained with the alternating system at least compensates for lagging current in the trolley wire or the extra expense of stringing and maintaining two trolley wires, if the polyphase system is used. We will compare the systems on the basis of the same loss of energy reckoned from generator to motor, since the efficiency of generators and motor is substantially the same throughout, and for simplicity will not figure out close details of distribution, but reckon the copper required in the simplest possible manner. The permissible loss of energy from generator to working conductor, we will take as fifteen per cent at maximum load, allowing five per cent loss in the trolley wire. We have already seen that if maximum load is taken care of, the average load will look out for itself.

In supplying current from two separate power houses these would naturally be placed 15 miles apart and 7½ miles from each end of the line. Each power house would then feed half the line, 7½ miles on each side of its location. The average distance of transmission would then be 3¼ miles, quite nearly 17,000 ft.

The maximum voltage for standard generators may be taken as about 600, giving with fifteen per cent loss 510 volts at the motors. Each station would have to be able to deliver 600 amperes at a distance of 17,000 ft., with a loss of ninety volts. Falling back on our stock formula

$$W = \frac{42 \times 600 \times 289}{90} = 80{,}920 \text{ lbs.}$$

At current prices (fifteen cents per pound) this would mean the expenditure of $24,276 for feeder copper for the two stations. The annual output for both stations would be about 2,000,000 k. w. hours.

The operating expense of two stations each of 300 k. w. maximum output would, of course, be decidedly more than if the output were concentrated in a single station. The extra expense due to this cause can be estimated with fair accuracy. With coal at about $3 per ton it would probably amount to 0.25 cents per kilowatt hour, the difference between, say, 1.5 cents per kilowatt hour with a single station and about 1.75 cents with the two stations. The total extra expense would be then about $5000 per year.

With a booster system the principal gain would be the ready use of the extra working voltage on the line. The motors could with advantage be run at 575 to 600 volts giving, say, 700 volts for transmission. The distance of transmission would, however, be doubled, as the best situation for the station would be the center of the line. Taking now the average distance as 34,000 ft. the current, reduced by the extra voltage, as 525 and the permissible volts drop as 105, we have as before

$$W = \frac{42 \times 525 \times 1156}{105} = 242{,}760 \text{ lbs.}$$

for the transmission in each direction, giving a total of double this amount costing at 15 cents per pound $72,628. The boosting apparatus would probably add $2500 to the cost of the station, and the cost per kilowatt hour generated would be as above, about 1.5 cents for 2,000,000 k. w. h. per year.

Now coming to the transmission systems proper, with a substation and rotary transformers the cost of the fundamental station, with double-ended generators would be about the same as for an ordinary continuous station. For the transmission there must be added a set of raising transformers of about 300 k. w. costing, say, $10 per kilowatt, and extra switchboards and subsidiary apparatus amounting to, say, $1000. The line will have the advantage of high voltage, but the drop will have to be small since the loss in transformers and the rotary transformer must come out of the fifteen per cent allowed as total. With the best efficiencies that can be expected from these the line loss must not exceed four per cent. The voltage of transmission may be taken as 10,000, hence the drop would be 400 volts. The copper must, of course, be figured as a complete metallic circuit, and the formula will become

$$W = \frac{4 \times 11 \times 3 \times C \times L^2_m}{V}$$

in this case the current may be taken as thirty-five to make allowance for residual lag and L_m is about sixty-eight. We get, therefore, for the transmission line

$$W = \frac{44 \times 3 \times 35 \times 1156 \times 4}{400} = 53{,}408 \text{ lbs.},$$

in all costing, at 15 cents per pound, $8012. At the substation there will be switchboards, transformers and rotary transformers for 300 k. w., which with the house may be lumped at $10,000.

Beyond these costs of transmission is the distribution system of feeders, which will cost the same as in Case I, together with the maintenance and depreciation of the transmission plant and labor at the substation, in all, say, $4000 per year. And even after this comes the fact that although the voltage on the working lines can be held within the fifteen per cent limit of loss, we still have the energy loss in the distribution system of feeders.

With alternating motors the case is very different.

The station generating apparatus has the same cost as before. The reducing transformers may be taken at \$4000. The whole feeder system would be at high tension, and there would be no need for raising transformers, since the fairly large station generators could well give 5000 volts and be overcompounded for, say, ten per cent loss in the line. The cost of machines for such voltage might be slightly higher, perhaps \$1000 on the plant. A like amount should be added for high tension switchboard and extra appliances. Now the total energy in this case is transmitted an average distance of 34,000 ft., as in the booster distribution. Using the same formula as in the preceding case we have, allowing ten per cent line loss, and fifteen per cent extra current to compensate for lag,

$$W = \frac{44 \times 3 \times 138 \times 1156}{500} = 42{,}078 \text{ lbs.}$$

of copper, costing \$6312. It is but fair at present to assume an extra cost of fifty per cent for the car equipments, say, \$500 per car for fifteen cars, in all \$7500.

We may now gather these data as follows :

Case.	Cost of copper.	Cost of Extra apparatus.	Cost of 2,000,000 k w h.	10 % on copper.	10 % on extra app.	Extra labor for working.	Sum of these anuual charges.
I.	\$24,276		\$35,000	\$2,427			\$37,427
II.	72,628	\$ 2,500	30,000	7,262	\$ 250		37,512
III.	32,288	14,000	30,000	3,228	1,400	\$2,500	37,128
IV.	6,312	13,500	30,000	631	1,350		31,981

These figures speak for themselves. In reality III is, under the assigned conditions, decidedly inferior to the others in efficiency, as already indicated. It can only be used economically under rather rare conditions, and then only in default of a proper alternating motor system. I and II are almost exactly equivalent, and very small differences in cost of power generation would throw the advantage one way or the other. IV is easily the best, and would still hold its position of superiority in the face of a considerably larger allowance for lagging current than that here made. With a smaller permissible loss of energy than fifteen per cent, the booster system would drop rapidly to third place in desirability, and IV would have even greater advantage than at present, while III would be out of the question. Any increase in the price of copper or decrease in the cost of apparatus would give a still further advantage to the alternating motor system. It should be noted that the tabulated figures do not in any case include the working conductors.

At all distances and losses a good alternating system would be in the front rank, and excepting at very moderate distances, would easily lead. One fact, however, must be remembered. An alternating current does not penetrate far into the substance of an iron conductor, hence in using an alternating system the rails cannot be counted on for their full conductivity. This would be very serious even at 25 ~ if it were not that the magnetizing force due to the current in the rails would under ordinary circumstances be so low that the permeability of the steel would be small, not over 200 to 300. At 25 ~ the equivalent conductivity of rails of the usual sections cannot safely be taken at over 0.5 the usual value, perhaps as low as 0.3. Fortunately, in the interurban and long distance lines for which alternating motors are most needed, the current density in the rails is likely to be so low that the permeability is kept down and the rails are still fairly good conductors.

CHAPTER VIII.

INTERURBAN AND CROSS COUNTRY WORK.

The most important class of electric roads at present is that composed of tramways that have outgrown and reached beyond their urban starting points and serve to interlink cities and villages. These lines are important and interesting to the engineer, since they are often subject to unusual conditions and require special treatment, and they are of immense value and importance to the public, because they tend to break down the industrial barriers that have been artificially established between city and country, and give to both some of the advantages now peculiar to each.

There is nothing in the nation's growth more menacing to good government and the healthy growth of industry than the rapid concentration of population and enterprise at a small number of overcrowded spots.

The opening of easy channels of communication through the country at large, increases enormously the areas available for profitable manufacture and decent habitation. Much has already been accomplished by the interurban and suburban electric railway systems already installed, and much more can be done by the extension of these lines and the building of new lines through regions that are now isolated.

Fig. 112, showing the connected system, of which Boston is the center, gives a vivid idea of the extent of country covered and the thoroughness with which the work of interconnection is done in certain regions. Still, large districts are left untouched, giving ample room for further extensions. The districts already interlaced, however, have an aggregate population of very nearly 1,250,000 inhabitants. And all this, with few exceptions, is the result of extension of strictly urban systems and not of independent effort at new avenues of intercommunication.

This character of growth is attested by the fact that of the entire network only the road from Lowell to Nashua, N. H., and the isolated Nantasket Beach road, differ in engineering features from the general practice on purely urban roads. Practically all the work is done in the ordinary way at about 500 volts. Of course, the *tout ensemble* is a shocking example of inefficient and costly distribu-

FIG. 112.

tion—the necessary result, however, of its manner of growth. Some of the component systems, of course, are beautifully designed.

Most existing roads of the interurban class have in similar fashion been the result of extensions, but recently there has been a tendency toward systems intended deliberately for interurban work, and designed with this in view. Such is the system about Cleveland, O., described in a former chapter, the recently opened line between Los Angeles and Santa Monica, Cal., and divers others. These lines are rapidly increasing in numbers and form the connecting link between street railways with their suburban extensions on the one hand, and electric systems replacing steam railroads on the other.

The distinction between these classes is somewhat artificial, but none the less real. We shall consider only those roads that are prepared to operate capacious trains at speeds of thirty miles per hour and upwards as really entering upon the functions of ordinary railroads. The strictly interurban roads have a function of their own, and a most important one, in linking together urban systems and opening up direct service between points previously connected very indirectly.

A glance at Fig. 112 will show that the latter function is even now very imperfectly fulfilled. There are still left great areas in which there is no intercommunication except by paying a double tariff into and out of one of the larger cities.

The cross country roads, as yet but little used in this country are destined to play a very important part in the development of our country. They should serve as feeders both for steam roads and interurban electric roads, forming the capillaries, as it were, of the industrial circulation. They are naturally allied to interurban systems, but owing to the necessity for cheap constructlon and the comparative unimportance of high speed, must be separated from them in engineering details and particularly in equipment.

The interurban road proper differs from the ordinary street railway in several very important particulars. First, the speed is on the average very much higher; second, the stops are relatively much less frequent; third, the average distance between generator and motors is far greater; and fourth, the average power per car is considerably more in amount.

As regards the first count, the actual speed on all electric roads is apt to be overestimated. Most cars on street railways have an average speed, including stops, nearer five miles an hour than ten, as can readily be figured from the hours of running and the average daily mileage. Now for runs between town and town much greater speed than this is desirable and can be readily reached in the absence of traffic obstructions.

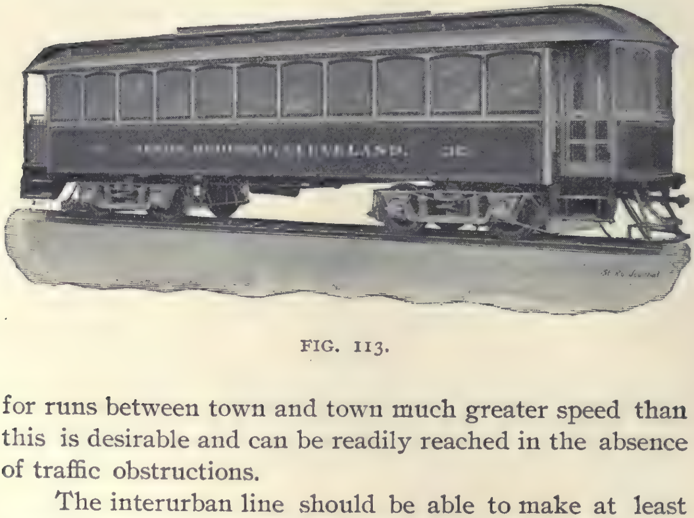


FIG. 113.

The interurban line should be able to make at least double the average speed of the street railway proper, and this means from twelve to eighteen miles per hour including ordinary stops. The maximum speed corresponding to this is likely to be from twenty to thirty miles per hour, seldom, however, the latter figure. The general running speed is likely to be between fifteen and twenty miles per hour, seldom the latter figure.

These speeds call at once for modifications of standard cars and trucks. Under such conditions the common single truck is positively unsafe on ordinary track, and recourse must be taken to double truck cars. The importance of this has been emphasized by several serious accidents from attempting high speeds with single trucks.

So in the natural course of evolution a fine type of double truck car, similar to that used on many large urban systems has come to be used for most interurban service. Such a car is well shown in Fig. 113. It is, save in size, closely similar to an ordinary railroad car, having the same general interior arrangement. It is forty feet long, vestibuled at one end, and is provided with special air brakes.

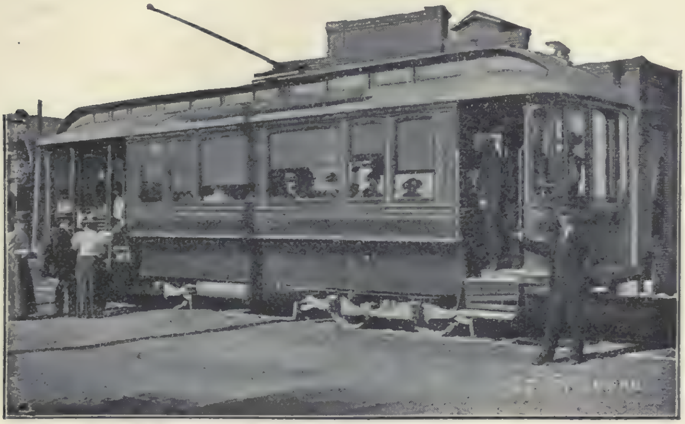


FIG. 114.

Another recent interurban car partly open and partly closed (a favorite construction on the Pacific Coast) is shown in Fig. 114. This is rather lighter and five feet shorter than Fig. 113, and like it is provided with air brakes.

At interurban speeds, electric or air brakes are almost a necessity and on the later roads are quite generally provided. As a rule too, the wheels are larger than the thirty-three inch size now standard on most street railways, thirty-six and forty-two inch wheels not being infrequent. These sizes give more room for the larger motors required and are better adapted for the cars.

As to track, careful laying and good ballasting are the essential points. The rails themselves are what would be used for a light steam railroad, forty to sixty pound T being the rule, although at the termini the usual girder rails often have to be employed. It should be remembered that a city track gets far more wear and tear than the average interurban track and must be, accordingly, even more substantial.

The rather infrequent stops in interurban work produce on the whole a tendency toward uniform distribution of load that operates favorably on the necessary distribution of power. The service is less liable to blockades, it is easier to hold to a regular schedule and there is less of the troublesome shifting of the load, than in street railway practice. Consequently it is somewhat easier to plan the feeder system.

On the other hand, the average distance to which power has to be transmitted is considerable, so that the aggregate amount of feeder copper is great, and it is aggravated by the frequent attempts to transmit power unreasonably long distances at 500 volts to avoid distributed stations or other appropriate methods.

The absolute amount of power required per car is, for an approximation, nearly double that required for a standard double truck car in street railway work. The speed of the interurban car is nearly double, and the car itself is often heavier. On the other hand the average live load is likely to be smaller and the power wasted in stopping and starting is less. On the ordinary urban railway twenty to twenty-five amperes per car is not far from the average power required through the day; on a busy interurban line forty to forty-five are likely to be required, or thirty to forty if the traffic be moderate.

Consequently heavier motors are often employed than on street railways, although for many cases they are unnecessary. If the traffic is likely to be large or if the speed is to be carried toward the higher limits mentioned extra large motors should always be used.

Figs. 115 and 116 show motors especially planned for interurban and similar work. They are of the usual General Electric and Westinghouse types respectively and may be classified as of forty to fifty horse power. They are fully up to the speeds and loads needed for heavy interurban service and are coming into extensive use for this purpose. In general construction and arrangement they are closely similar to the standard street car motors of the same makes, and are habitually worked with series parallel control, which may properly be considered a necessity for economical operation. The saving by such control in interurban work is, of course, less than usual, since the motors are in parallel most of the time, but the device is very necessary to bring the speed within reasonable limits in running through towns.

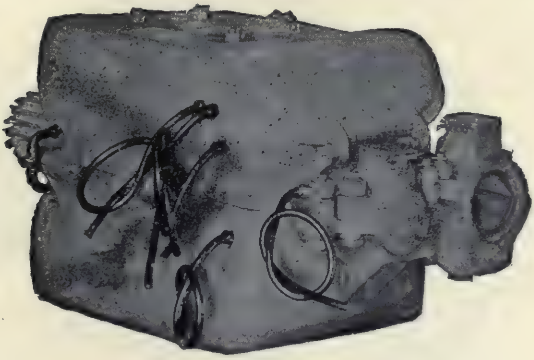


FIG. 115.

Except for the unusual size of the motors and the general use of power brakes there is little peculiar in the car equipment necessary for interurban work. The trolley and its connections are quite as usual and the method of operation is unchanged.

The trolley wire, too, is of the same character and suspended in the same way as for ordinary street railway work.

It is advisable, however, to use a larger trolley wire than usual, not at all to secure larger area of contact with the trolley, for this is needless, but to simplify the feeding system. The larger the trolley wire, the easier it is to equalize the voltage along the line. Nothing smaller than No. 00 should be used and No. 000 or No. 0000 may often be useful. These larger sizes require special precautions in suspension. but sometimes are worth the trouble. In most interurban work the bracket suspension can be freely used and is advisable, being cheaper and easier to keep up than the crosswire suspension.

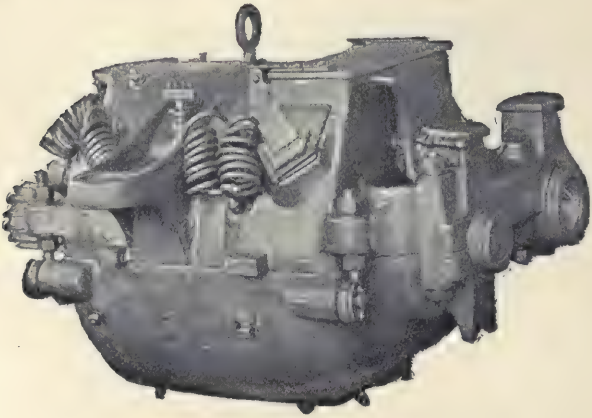
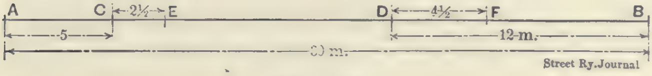


FIG 116.

The supply of power to an interurban line can best be illustrated by working out the details of a concrete case. We may take for this the hypothetical line discussed at the end of the last chapter, selecting for discussion the first case, using two stations for the line.

Fig. 117 is a diagram of the system. Here A and B are the termini, C and D intermediate towns which may have an influence on the distribution of the power and E and F the points selected for the power stations in Chap. VII. The track is, as will usually be the case in such roads, a single track with turnouts. The distance from A to B is thirty miles, from A to C about five miles and from D to B twelve miles. In the previous discussion the load was assumed uniform along the line. Obviously it is unlikely to be so, and we must accordingly modify the simple arrangement there shown. We may still allow the fifty amperes per car as before. The exact effect of C and D on the interurban traffic cannot possibly be foretold, and indeed it will constantly be subject to some variation, nevertheless certain things can be safely predicted.

The local traffic between C and A will have the effect of shifting the load centre of the section, E A, toward A. Similarly the traffic between D and B will shift the load on the right hand side of the section, E F, somewhat toward F. If the towns, C and D, are of nearly the same size, the two halves of the line will be about equally loaded, so that the stations will be of the same size. E D will assuredly be the most lightly loaded section of the line.



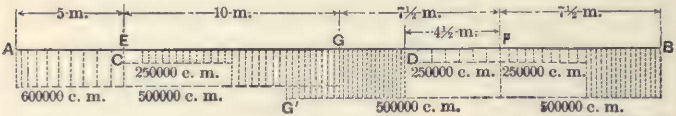
Street Ry. Journal

FIG. 117.

Now what conclusion as to the distribution of power are we justified in making? Although some data are available as to purely urban traffic in cities of known size, there are as yet no data for predicting the probable actual travel on an interurban line. The assumption as to current required is as close a guess as one would be justified in making. Any change in the distribution of feeder copper, due to assumed differences of load in different parts of the line, is somewhat hazardous, and about the only change authorized by the evidence is a change of position of the station, E. A situation at or near C is certainly an improvement. It might be advantageous to make F equidistant from D and B, but in view of the shift in E it probably would not be desirable to further increase the distance between stations. Throughout we assume that the real local traffic over our line in A and B is small, owing to local street railways.

We may now lay out the system as shown in Fig. 118 and plan the stations and feeders. We have two stations, E and F, of equal size, each supplying half the whole line, A B. The station, E, however, serves a line five miles in one direction (E A) and ten miles in the other (E G) to G, the center of the line. The station, F, feeds 7½ miles each way. Each of these stations must be able to furnish a maximum current of about 600 amperes and an average output of about half this. The voltage should be as great as the standard generators can conveniently give, say, 600 volts as a maximum.

If we are, as in the previous discussion, to allow fifteen per cent loss at full load, ten per cent in the feeders and five per cent in the trolley wire, the generators may well be given an overcompounding for ten per cent, thus taking care of the loss in the feeders.



Street Ry.Journal

FIG. 118.

Each station should be equipped in duplicate, partially at least. The maximum continued output at any time we have assumed at 360 k. w., 600 amperes at 600 volts. The average output is about 180 k. w. and, save at special times, the maximum output would be considerably less than that noted above. If at each station were installed two generators, of 225 to 250 k. w. output apiece, one of these would handle the whole load of the station during a considerable part of the day, and the second could be thrown in on the heavy hours or all day on special occasions. In case of accident to a dynamo or an engine the remaining one could keep up the service without serious interference with traffic, particularly if the feeders were arranged judiciously.

As regards the arrangement of these units it is rather an open question between direct coupling and direct belting in a plant of this size, with, perhaps, the weight of advantage rather in favor of the former alternative. At this output, however, one is quite near the point at which the construction of direct coupled machines becomes embarrassing on account of low speed, and it often happens that the belted plant is not only cheaper, but more efficient. It most emphatically does not pay to couple directly to a simple, non-condensing engine, instead of belting to a Corliss type engine in a plant of this size. It always pays to condense, and it nearly always pays to use compound engines. The simple, single valve, non-condensing engine is an economic abomination in such a plant, and should not be considered for a moment. The author's choice would be a compound condensing engine, with independent admission and exhaust valves, running not less than 120 to 150 r. p. m. Such an engine plant will produce power at about two-thirds the cost by ordinary simple engines, and very nearly as cheaply as the best that can be done under similar circumstances by the best triple expansion engines which, in a plant of the size considered, are less suited to the conditions of variable load than compound engines.

We may now take up the distribution step by step. For a constant we may safely take 14, as representing the case of a good track and moderately heavy traffic.

Beginning with the section E A, we may safely assume that about one-fourth the total load will be concentrated upon it, and uniformly distributed. We will assume a No. 000 trolley wire of 167,000 c. m., weighing 2677 lbs. per mile. This wire will carry 100 amperes, the maximum current for a single car, over 4000 ft., with moderate loss of voltage. Three cars normally belong on the section, and we must meet the contingency of all three being at A and loaded, calling for, say, 200 amperes. In this contingency we should be justified in assuming as much as 100 volts drop in the feeders alone, and that not more than one other car will be fairly upon the section. At five miles distance the delivery of 200 amperes under these conditions calls for 728,000 c. m. This may be very advantageously approximated by a 600,000 c. m. cable plus the trolley wire. If this cable is tied into the trolley wire at frequent intervals, say, every 1000 ft., for a mile or two near A, the drop in the trolley wire as such becomes trifling, and the drop saved here may be transferred to the feeder account. Nearer E the taps need not be so frequent, and the trolley wire should be directly connected to the station. We may then arrange this section as shown in Fig. 118 by the dotted lines. Under this arrangement the drop at normal full load, with one car at A, a second nearly midway between E and A, and another near E, assuming for current 100 amperes per car would be pretty near the required fifteen per cent, although, as we have previously seen, the conditions of extreme load must in the last resort determine the amount of feeder copper.

A feeder of 600,000 c.m., uninsulated, weighs 1800 lbs. per thousand feet (three times the circular mils in thousands, as we have already seen), hence we must write down against this section about 48,000 lbs. of copper.

Next comes the long section E G. On this three or four cars may normally be operated. About the worst that can be expected is a couple of cars near G calling for perhaps 150 amperes together and a similar pair fairly near E. As to drop we may here take rather extreme measures and allow, so far as station E is concerned, a maximum drop of 150 volts. This calls for 770,000 c. m. which we can again make up of a 600,000 c. m. cable plus the trolley, the two being frequently tied together. But even this does not properly take account of the second pair of cars. These at worst cannot be expected to be more than five miles from E. Hence under the same conditions of drop the total area of copper required would be 385,000 c. m. In connection with the trolley wire a 250,000 c. m. cable would be rather more than enough to do the work. This feeder should be tied to the trolley perhaps every 1000 ft., and should cover the first half of E G. This pair of feeders, as shown in Fig. 118, complete the distribution system for the station E. The main feeder here would weigh about 96,000 lbs. and the short feeder about 20,000.

We may now take up the station F and its connections. F is midway of its section and the only disturbing factor is a small one, the town D. Its tendency would be to move the load center of the section G F toward F since a town in such a situation would probably be tributary to B rather than A.

The section G F would normally contain three or at most four cars. The worst concentration of load to be expected would be a pair at G with another pair between D and F. Allowing 150 amperes for each pair and a maximum of twenty-five per cent drop to G, we find about 600,000 c. m. required. But G can draw part of its current from E. Therefore we can take advantage of this fact and not only use less copper from F to G, but reduce that from E to G. Altogether we are unlikely to get more than three cars in the vicinity of G calling for, say, 200 amperes. This would call for only about 1,000,000 c. m. from both stations. Since it is desirable to give one station the ability to extend some help to the other it is desirable not to cut down the copper too much. One of the most practical ways of doing this is that shown in the figure. Reducing the main feeder from E to G to 500,000 c. m. we run a similar feeder from F out to and beyond G, making the two feeders of the same length. This leaves on the section G F two cars unprovided for. As there may be an occasional call for extra conductivity toward D, this section may well be provided for by a 250,000 c. m. cable up to D.

The 500,000 c. m. feeder weighs 1500 lbs. per M feet, and there is ten miles of it, weighing, say, 30,000 lbs., which is also the weight of the revised feeder from E to G. The 250,000 c. m. feeder weighs 750 lbs. per M feet and its total weight is about 15,000 lbs.

We may now pass to the final section, F B. The conditions at B are similar to those at A. Allowing 200 amperes possible demand near B, about 750,000 c. m. will do the work there. There may be, however, a car or two elsewhere on the section at the same time, calling perhaps for one hundred amperes.

The joint load can be best taken care of by a pair of feeders, one to B of, say, 500,000 c. m., the other out, say, four miles from F, of about 250,000 c. m. The function of the latter is to handle cars within that distance of F and also to improve the conditions at B. These are shown with the rest in Fig. 118. The weight of the main feeder here would be 60,000 lbs., that of the small feeder, say, 15,000 lbs.

We can now take account of stock and find the total cost of copper for the feeding system. We may tabulate as follows:

Section.	Wt.
A E	48,000
E G (main)	80,000
(adjunct)	20,000
G′ F (long main)	80,000
adjunct	18,000
F B (main)	60,000
adjunct	15,000
	321,000

This would cost at fifteen cents per pound about $48,000, a very different figure from that previously found by the assumption that the maximum load may be taken at the middle point of the proposed line to be fed.

The existence of this excess and the causes that produce it must be carefully examined. In the first place 20,000 lbs. of copper, the section of feeder G′G belonging to station F, is directly chargeable to safety precautions, and is for the purpose of enabling the two stations to be of some material assistance to each other in case of accident to one of them.

The large remaining discrepancy is almost wholly due to the fact that the load on an electric railway is a shifting one. Instead of being able to assume a uniform distribution of the maximum load, it must be treated as a concentrated load, perhaps even at the most unfavorable point of the line. In fact, it often happens that the maximum load must be handled at the extreme end of the section, instead of the middle point. Since the copper required varies as the square of the distance, this extreme position would require four times the copper called for under the original hypothesis, but on the other hand for this abnormal load much more than the average drop is allowable.

In this as in all other railway work the real investment in copper is determined not by the average loss of energy that may be desirable, but by the maximum drop permissible under the worst conditions of load. This condition weighs heavily on interurban lines, since where a network is possible, the various parts of it will not be loaded simultaneously and can help each other out, while on a straightaway line each section of conductor must act for the most part independently. In a long interurban road of this character the booster may often find a legitimate and important use. If we could depend on a fairly uniform schedule of traffic the practical arrangement of the feeding system would be much simplified. In cases like the one in hand there are likely, in spite of careful operation, to come times when cars are massed at one point on the line to an extent not contemplated in the design of the system.

Suppose for example that occasionally extra cars must be run between A and B. A circus comes to the latter place or some special celebration takes place there and it becomes necessary to accommodate a very unusual number of passengers within a limited time. It may then be very important to deliver double the usual maximum current, say, as much as 400 amperes, at B while still retaining a good working voltage. This the existing feeders would be quite inadequate to maintain, since the drop would be in the vicinity of 300 volts.

To bring the working pressure to about 500 volts, which would be highly desirable to meet this exigency, would require the installation of something like 75 tons of copper, costing about $22,500.

The best alternative is to install a boosting dynamo at the station F, to furnish about 200 additional volts on the long feeder, F B. The capacity of this booster should be about 100 k. w. and its cost, complete with motive power, and ready to run would not be more than $5,000. This would enable the voltage to be kept up at B under most trying conditions, and would moreover enable station F to be of great assistance to station E in case of accident to the latter. A similar booster at E would be able to render similar service at F and to take care of the most abnormal loads at A. Ordinarily these boosters would be in service only at infrequent intervals, a few hours per day for a day or two at a time, but they would be well worth installing merely as a precaution, insurance as it were.

If the loads on the line become such as to require frequent aid from the boosters the economics of the case would have to be looked into as indicated in Chap. IV, and it might prove to be wise to install additional copper. In all roads of this class the local conditions must ultimately determine the character of the feeding system for the most economical results.

In spite of this the copper required in the case in hand is not very formidable. Unless the road is operated on a regular schedule, still more copper would be required, since if the operation of the cars is careless and irregular, more may be massed at a single point than were allowed for in the estimate. For economy in copper the road must be intelligently operated as well as skillfully planned. The same uniform schedule that secures good and regular service throughout the line will facilitate good and economical distribution of power. The only reasons for unusual massing of cars at one point are accidents to the track or motors or very unusual demands for car service. In the former case, the service can be resumed on regular time without any extraordinary demand for power, and in the latter there will be no trouble if any extra cars that may be necessary are run in an orderly manner, as they would be on any well conducted railroad. Managers should bear in mind that the operators on an important interurban line should be picked men of more than usual skill and intelligence, and that it pays to get such men. They are worth the extra cost merely as a form of insurance.

No general rule can be assigned for the increase in feeder copper due to the demands of heavy displaced loads. The amount and character of the displacement varies in different cases in a way that cannot be formulated. The only thing to be done is to take up each case as a special problem as we have just done.

The effect of this extra copper on the relative economy of the various methods of supply is easy to approximate. Recurring to the estimates at the end of the last chapter, it is evident that they need revision. The annual cost by method I will be increased by the interest and depreciation on the additional copper. Method II will suffer in almost the same ratio as method I, and hence the absolute increase in copper and the added annual expense will be greater, putting the booster method to very serious disadvantage, if used without undue loss of energy except as it may be adopted for emergencies, as just described.

Method III, which really consists in transmitting power at high voltage from E to F (Fig. 118), is affected to precisely the same absolute extent as method I, and therefore has practically the same relative value as before.

Method IV must take into account the same conditions of displaced load that influence the other cases, but in a somewhat different way. The trolley wire alone is unable to carry the current for a severe load any considerable distance, hence it must be reinforced unless the line is to be supplied with an exaggerated transformer capacity and the transformers are placed very near together. To give a good practical distribution of power there must be sufficient feeder capacity to easily carry the current for the extreme loads already mentioned without demanding transformers at too frequent intervals. The net result of the conditions of load will be, first, to demand the installation of feeder copper to distribute the energy delivered from the transformers, and second, extra transformer capacity enough to respond to the utmost calls of a displaced maximum load In the case before us it would not be wise to subdivide the transformer capacity greatly, since the individual units would be small and expensive. The maximum load of 1200 amperes at 500 volts will be increased somewhat by lagging current, and no part of the line can be left without transformer capacity enough to take care of the heaviest load to be met. Consequently the total capacity of the transformers will certainly be much greater than the nominal 600 k. w., probably at least one-half greater. Without going far into details, feeders of not less than 250,000 c. m. would be needed to reinforce the trolley wire for its entire length. These would cost about $18,000 and in addition the extra cost of transformers due to their moderate size and extra capacity could hardly aggregate less than $5000 more. Hence an annual charge of about $2300 must be added to the annual cost of power obtained in the last chapter. This leaves the distribution by alternating current in the same relative position of advantage as before, a position which is the stronger as the distances to be covered grow greater. Only when the service undertaken is exceedingly heavy can distributed stations compete with a good alternating transmission, and the latter always has the possible use of water power or utilization of cheap coal to its credit.

A very striking instance of the value of transmission to alternating motors is given by the Burgdorf road described in the last chapter. Here full advantage is taken not only of the economies of transmission but of the facility with which polyphase motors may be worked at voltages considerably higher than 500 volts. The result is that in spite of a heavier load than is here assumed, no low tension feeders are employed and the total cost of copper is hardly more than we have here taken for the cost of auxiliary feeders alone.

Allowance must be made, however, for the fact that in Switzerland copper is more expensive and transformers are materially cheaper than in this country. Here the legitimate tendency would be to use fewer transformer stations and more copper than in the foreign case.

With 750 volt motors the weight of copper required for the distribution would come down to about one-half of that which we have assumed and the whole amount could be conveniently placed in the working conductors. As to number and location of transformer stations, the most beautiful feature of the whole method is that these can be placed, without any material variation of cost, just where they will do the most good. On the road that we have assumed for investigation the most advantageous number would probably be somewhere between six and ten. The natural locations would be near A, B, C and D respectively, between C and D, and between D and B. The distribution in number and position would be governed by the distribution of the load. It may often be convenient too, to vary the size of the individual transformer stations so as to best meet local conditions, and the system as a whole is wonderfully economical and flexible.

Very different in character, but nevertheless allied in function to interurban roads are those which we have designated as cross country roads.

It is surprising to realize how small a part of this or any other country is conveniently tributary to existing railway lines of any kind. A glance at the map of any well settled state will show many townships not touched by any railway and many more only reached in roundabout ways. It is not uncommon to find a rich farming district almost without means of communication with neighboring cities and totally devoid of facilities for intercommunication betweens its parts save in the good old fashioned way. Nearly one-seventh of the towns in Massachusetts are without railway stations. Within fifteen miles of Boston is one whole township untouched by a railway of any kind, steam or electric. In the less populated states, there are many fine regions that are quite isolated.

Railroads have left these regions untouched because a route elsewhere would pay better, or would give prospects of traffic sufficient to float a heavier capitalization without creating undue suspicion.

There are, of course, plenty of cases in which an ordinary railroad, even a branch, would not pay and consequently is not built, while the prospects of traffic are yet quite near the paying point. A railroad is a rather inflexible thing at best. It requires a nearly level track, must avoid severe curves, has often to acquire an expensive right of way and is in general subject to restrictions and limitations in such wise as to render construction and operation somewhat too costly for many places that are yet in the aggregate of considerable importance. Especially in the agricultural regions there is much rather scattered freight traffic which cannot be easily handled by an ordinary road at paying rates, but could be profitably gathered and increased by roads built with this specific object in view.

Abroad much has been done in the way of building light railways especially for the purpose of developing agricultural districts. Most of them are narrow gauge, between two and three feet, although a few conform to the existing standard gauges for convenience in exchanging and transmitting cars. In Belgium and Prussia especially this class of service is very considerable in amount, although there are roads of this kind all over the Continent and not a few in England and English colonies. Owing to foreign habits of railway construction most such lines are from our standpoint too expensive, costing in general from a minimum of $7500 to $15,000 or more per mile to build and equip.

In this country there was fifteen or twenty years ago an epidemic of narrow gauge construction, generally resulting in a change to standard gauge.

The truth is that while these light, narrow gauge railroads can be built and equipped quite cheaply, often for half the cost of standard construction, they are seldom cheap enough to give much advantage when they attempt serious railway service. In competition with regular lines, they soon find themselves handicapped, and for purely local purposes they generally are too costly.

The need in very many cases is for feeding lines to facilitate the movement of commodities and passengers now laboriously hauled over country roads. For this specific purpose the first consideration is cheapness; these lines would not come into competition with existing railroads, hence there is no need for more than very moderate speeds; there is no need of handling heavy trains; light passenger cars and freight skips are quite sufficient. The moment one attempts to use standard gauge and exchange cars with through lines heavy construction is necessary to stand the wear and tear, and the cost becomes too great for the purpose in hand.

For this cross country service electric construction is singularly well suited. Grading, always an item of expense to be feared, is much reduced with an electric road, for while two or three per cent grades are all that would be attempted in ordinary light railway construction, ten per cent is perfectly practicable for an electric car with a light trailer or two.

A gain equally important is the weight of the motive power. Instead of a locomotive weighing six to ten tons, the dead weight of the motor need not much exceed half a ton, which, with all the load in the motor car, is available for securing adhesion. With this lessened weight to be carried the track construction can be lightened and cheapened correspondingly.

In spite of the singular fitness of electric service for this particular and most useful purpose, little has as yet been done. Perhaps the reason is lack of popular appreciation of the exact conditions to be met. The danger lies in trying to do too much, in building an ordinary cheap electric railroad, instead of something little more elaborate than a telpher line; in trying for a speed of twenty miles per hour where ten is amply sufficient.

To meet the need of small places for transportation facilities one must cut his coat according to his cloth. A little hard common sense applied to the problem will result in the establishment of many a most useful line, giving greatly increased facilities for intercommunication, and yielding good returns on a small investment.

A standard gauge (4 ft. 8½ ins.) electric railway track can, if the grading is trivial and the route is generally easy, be put in position for a total cost of as little as $5000 per mile of single track, exclusive of bridges and other special construction and right of way, using ordinary cars and car equipments. This supposes T rail of forty to forty-five pounds per yard and economy everywhere. The cost of overhead wire, bonding, equipment and station per mile, of course, depends entirely on the service. For a road, say, ten miles in length, very economically equipped, $4000 to $5000 per mile may be enough. In other words, the cheapest feasible price for building and equipping a standard gauge electric road is somewhere about $9000 to $10,000 per mile, anything under $10,000 being extraordinarily low.

Now for the work properly belonging to cross country roads that figure is often prohibitively high. In order to do the work at a less price, radical changes have to be made in the structure. For localities where grading is slight, and there is not likely to be much trouble from snow, light, narrow gauge roads meet the conditions fairly well.

Foreign practice gives valuable data in this line. For a gauge of 0.6 metre frequently used abroad (practically two feet), a rail weighing about twelve kilos per metre (twenty-five pounds per yard) is freely used. The substructure can be light in proportion, for the rolling stock is also light, albeit the locomotives are decidedly heavier than a loaded motor car would usually be. We must remember that with light cars, comparatively low speeds and rather infrequent service, a light rail can be safely used, and will give no more trouble than heavy track under ordinary street railway service.

A twenty-four inch gauge track, laid with thirty pound rails, can be put down under favorable circumstances for about $3500 per mile. Then comes the bonding and the erection of the overhead structure. The amount of wire required for such a line is comparatively small, for the power also is small.

For a line ten miles in length, two trains in steady service, each consisting of a light motor car and a freight skip, would meet all ordinary requirements. The total weight, loaded, should not often exceed ten tons. To drag this load on a level track at eight miles per hour requires about seven horse power at the car wheels. As grades would naturally be taken at a somewhat lower speed, the power required would not increase very greatly, and an expenditure of fifteen horse power at the wheels would seldom have to be exceeded.

FIG. 119.

In reckoning the copper we should have to allow for the delivery of about thirty amperes to the train. With 600 volts initial pressure, and allowing one hundred volts drop at the end of the line, it appears that the copper required is trifling. Using 13 as the constant in our stock formula, the wire, supposing the station to be at the center of the line, comes out No. 0, which may conveniently be suspended as the trolley wire.

For economy bracket construction should be used, unless circumstances require cross suspension, in which case the very neat diagonal suspension, due to J. C. Henry, is the cheapest and most convenient method for light work. This is shown in Fig. 119. Here A, B, C, D, E, etc., are the poles set in the usual way, 100 to 125 ft. apart, but alternately on either side of the track. The suspension wire is strung from pole to pole, as shown, and the trolley wire hung from it in the ordinary manner. It is a very neat and cheap arrangement where only a trolley wire of moderate size has to be carried. For either this or bracket construction fifty poles per mile are sufficient, costing, laid down, say, $125. Setting in country districts ought not to cost more than $1.50 per pole, bringing the pole line in place to about $200 per mile. The trolley wire would cost about $275 per mile, and suspension wire, insulators, brackets and so forth, about $200 additional, making about $675 per mile for overhead structure and material. For bonding the track and suspending the trolley wire, together with incidental expenses, $300 to $400 per mile is sufficient.

Bringing these items together we may say roundly that with rigid economy $900 to $1000 per mile will provide the electrical structure and connections for such a road as that under consideration. Taking the larger figure we see that the electric narrow gauge track can be built complete ready for traffic for about $4500 per mile.

For a ten mile road, the car equipment should be, say, two motor cars with an extra motor in reserve and four freight skips and a couple of freight cars of a larger size. The whole outfit should not cost over $5500 delivered and ready for action.

Now for the station and other equipment. A generator of, say, forty kilowatts, and a fifty horse power engine and boiler equipment is sufficient. Boiler and engine should be of the simplest kind and the whole plant as compactly arranged as possible, since it should ordinarily be operated by a single capable man. Engine, boiler and generator set up ready for operation should not cost in the aggregate more than $4000. This is enough to provide a thoroughly well built, durable equipment on which the repairs should be very light.

A combined power station and car house, with iron stack for the boiler, should cost complete not over $2000, and $500 more would provide waiting rooms and freight platforms at the ends of the line.

Altogether these items of construction and equipment would aggregate $12,000, or $1200 per mile.

Bringing together the various items reduced to the basis of cost per mile, we have for a ten mile road:

Roadbed and track	$3500
Electrical construction	1000
Rolling stock	550
Power station and buildings	650
Total	$5700

An addition of $300, bringing up the total cost to $6000 per mile, would provide for all normal contingencies of construction. It is safe to say that in most situations a good narrow gauge electric line can be built and equipped for this sum if right of way can, as would nearly always be the case, be obtained along the public road.

This is a reduction of about $4000 per mile over similarly close figures for a cheap ordinary electric road, a difference that would turn the scale from loss to profit in many country localities.

The cost of operating such a road is correspondingly low. The hours of running need not be eighteen or twenty as in street railways, but could be so reduced that the work could be arranged for a single set of men without unreasonably long hours. A total force of six men could operate the line without difficulty. Of these two, the engineer and superintendent who should understand the motors and linework well, would probably have to be paid $75 per month each; the other four could be obtained in most country districts for about $45 per month each.

Under ordinary circumstances the mechanical output at the station would not exceed, say, 250 h. p. hours per day. Counting five pounds of coal per horse power hour the daily fuel consumption would be a little over half a ton of coal per day costing, at $3 per ton, in round numbers $600 per year. $400 per year more should cover ordinary repairs and incidental expenses at the power station. Another addition of $500 should cover taxes and miscellaneous expenditures, making in all very nearly $5500 per year as the total expense account, irrespective of depreciation and interest.

Roads such as we are considering have the advantage of being able to charge relatively more than urban lines, and with a tolerable passenger service, express and mail service and freight traffic should be able to pick up a very satisfactory living. The ten mile line in question must show gross earnings of about $9000 per year to pay a fair return on the investment and set aside a tolerable sinking fund—practically $24 per day, or $12 per train per day. As each of the two trains should make six or eight single trips per day it appears that the road would pay on gross receipts of $2 per trip, twenty cents per train mile.

FIG. 120.

It is a lean region indeed that cannot furnish that amount of patronage.

But this is by no means the last word on cheap cross country lines. It is quite certain that there are available constructions cheaper than the narrow gauge just described. At least two existing arrangements are capable of a lower minimum cost of construction than that mentioned. Curiously enough both of them have been zealously exploited for heavy high speed railway work for which they are not in the least needed, instead of being pushed into a most useful field to which they are well adapted and in which they have decided advantages.

One of these is the well known "Boynton Bicycle" road of which an excellent idea is given by Figs. 120 and 121.

Fig. 120 shows the appearance of the construction across the country. Fig. 121 shows an end view of the narrow, pointed car in position on the single railed track. The upper bearing carried by the brackets extended from the heavy side poles along the line is merely a steadying rail whose function it is to hold the car upright when at rest and guide it around curves when in motion. In normal running the pressure against this upper guide is trifling. All the weight is carried by the central double flanged wheels on the track rail. The cuts are from pho-

FIG. 121.

tographs of the experimental track on Long Island. The apparatus here was on a considerable scale, as high speed was attempted without conspicuous success, probably owing to a track too short for speed.

Nevertheless, a glance at the cuts shows how readily and neatly the system can be applied to cross country roads with light cars operated at very moderate speeds. Under these circumstances the upper supporting structure having little strain upon it can be light and cheap, while a mere row of short posts rising just far enough from the ground to assist in the grading may serve to carry a light but rather deep girder rail, quite strong enough for the traffic. The rails would serve admirably as conductors since even a fifteen pound rail is far more than the equivalent of the copper required and the lower rail being off the ground would be little troubled by snow in winter. The supply of power is thus very easy and simple and the cost of grading is in great measure averted.

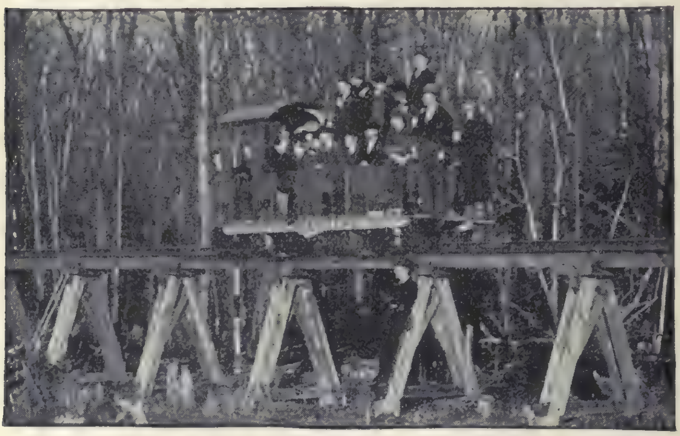


FIG. 122.

Another construction which can be carried out very cheaply on the scale necessary for cross country roads is the saddleback railway. The Meigs elevated structure is a good specimen of this type, which has been successfully worked up as an electric line in the Beecher railway, an experimental section of which has been put in use near Waterport, N. Y.

This arrangement is shown in Figs. 122 and 123 of which the first shows a car on the experimental track, and the second gives the essential details of the structure.

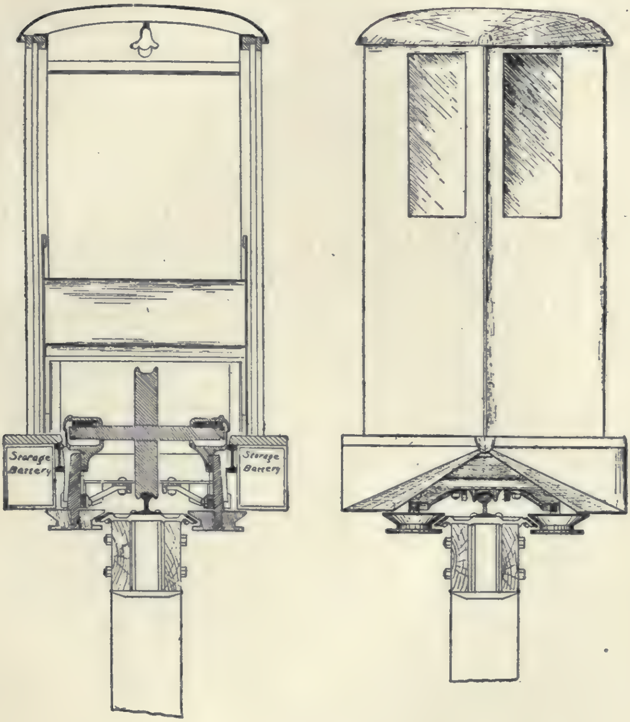


FIG. 123.

It is, as shown in Fig. 123, a quasi-elevated road composed of posts or similar supports carrying longitudinal stringers which support the central bearing rail and the lateral guide rails. These latter serve to steady the car, but are under very little stress when the car is in motion.

As in the bicycle railway, very little grading is necessary—none under favorable conditions—the rails serve admirably as conductors, and the supporting structure is cheap and simple. In the experimental road storage batteries were used, thereby throwing away one of the essential advantages in the conductivity of the rails and adding unnecessary weight to the car. For cross country working such a system should be a decided success since it could be carried high enough to be out of the way at crossings and takes up singularly little room.

Either the bicycle or the saddleback road can be installed even more cheaply than the narrow gauge line just discussed, owing to the practical abolition of grading, freedom from an overhead trolley construction and full utilization of the rails as conductors. These roads too are much less liable to trouble from snow and bad weather than the narrow gauge and are equally efficient for the purpose in hand. Under favorable conditions they could be built and equipped for the same service as the narrow gauge for a sum scarcely, if at all, exceeding $5000 per mile for a ten mile line. At a pinch any one of these roads could get along with one man per train exclusive of the men at the power house, thereby giving an electric railway, of which the necessary expenses would be hardly more than $4000 per year, and which would pay fairly on gross receipts as small as $7500 to $8000 per year. The possibilities of such roads for opening up the country are self evident.

Throughout the estimates just given it will be noticed that nothing is included for franchise and right of way. This omission is for the very good reason that in the regions to be benefited by such roads, franchise and way would always gladly be given, with not infrequently a substantial bonus in some form or other.

Built for cash and operated for profit, such roads offer good prospects for excellent returns on the investment, and their economic value to the country can hardly be overestimated. Almost nothing has yet been done in this line, but the field is a most promising one.

CHAPTER IX.

FAST AND HEAVY RAILWAY SERVICE.

Up to the present time a large proportion of all electric railway work has belonged strictly to street railway service, a few per cent can be classed as interurban, and only here and there have there been any serious attempts to beat the locomotive on its own ground. The task is a serious one not to be undertaken without good cause. Our present locomotive is a wonderfully reliable and efficient machine, beautifully adapted for its work, and if it is to be replaced by the electric motor, there must be good cause for the change.

The economic relation between the motor and the locomotive has been several times carefully investigated with the uniform result of showing, assuming the same conditions, no very considerable advantage on either side. It is in the variations in the conditions, the exigencies of traffic of different kinds, that positive economies in favor of electricity or of steam must be sought.

Without taking up the application of electric power to universal railway work, there are three classes of service for which it is now admittedly highly desirable, irrespective of any saving reckoned on the horse-power-hour basis, which does not completely tell the story of ultimate profits.

In general these three classes have this in common, that in each of them electric power gives positive advantage in earning capacity, aside from the saving in operating cost which certainly exists in two of them. The classes in question are as follows:

1. Heavy local passenger traffic.
2. High speed interurban traffic.
3. Elevated roads, tunnels, and special service.

In the first case experience has already taught the magnitude of the inroads made on local passenger service by electric railroads covering the same district. A striking example of this has recently come to the author's notice, in which a short steam road was actually deprived of more than ninety per cent of its traffic by the operation of a parallel electric system. Near every large city the effect of this competition is severely manifest and is doubly serious by reason of the increasing network of electrics that serves its territory so effectively as to overbalance the extra speed of the railway trains.

That which decides the route of the suburban passenger, in the absence of any great inequality in fare, is ultimately the time taken to travel from his home to his place of business. Convenient termini offset superior running speed, and the electric cars consequently catch the greater part of the traffic. Then too, in the time of the journey must be included probable delays.

The net result is that where electric cars and steam railways come into competition for suburban or similar business, the former gets the lion's share. To give good local service, the cars or trains must be frequent, the running time fast and the passengers must be delivered somewhere near where they wish to go. In most cases steam roads cannot meet the latter requirement, consequently they must compensate for its lack by fast and frequent service. This means short trains run on short headway, and right here the locomotive is at a serious disadvantage. In the first place the experience of railroads has shown that with increasing numbers of trains the cost per passenger mile increases. For a given amount of traffic carried in a certain territory, doubling the number of trains increases the cost per ton mile something like fifty per cent.

That such must be the case is easily to be seen, since the number of passengers per train is halved while the labor per train remains substantially the same, the power per train is not very greatly decreased, and the investment and depreciation are increased by using more locomotives for the same service. In point of fact for passenger service alone the cost per passenger handled would be nearly doubled by doubling the number of trains. If at the same time the running time were to be quickened there would be a still further increase of cost. Largely increased total traffic gives the only opportunity of squaring accounts.

In this heavy local work electric traction has very great advantages. The distances are usually moderate, so that all the power can be easily distributed from one or two power houses. The service too, is so dense that the station can be kept well loaded a large part of the time, and consequently working at a high plant efficiency. Hence the total efficiency of the power supply is great, while the absolute amount of power required is considerably less with electrics than with locomotives, since the former do not have to carry their power stations upon their backs. The results of actual competition have shown the desirability of electric working for suburban passenger traffic, and the character of the service to be given is tolerably obvious. It is necessary for the railway company to take advantage of the weak points of its competitors. Electric street railways have the advantage in the matter of termini and cover their field thoroughly. In speed, however, they are necessarily somewhat deficient and are liable to blockades causing very annoying delays.

Hence it should be the object of a competing railway by running frequent trains at high speeds to gain enough time for its passengers amply to compensate them for the time lost in walking at the ends of their route. It is specially necessary to retain the advantage at moderate distances, say, up to five miles from the center of the city, for here the competition is the most severe. Frequent express trains, while very useful in extending the exterior service, cannot regain the traffic lost within the effective sphere of the street railway.

The electrical problem is then to provide frequent trains capable of accommodating one or two hundred people each, running at a speed of twenty-five to thirty-five miles per hour, including stops.

In the present state of the art, this is not a serious matter. The only material difficulties that have been met in practice are those connected with the delivery of the necessary current to the moving car, and these are not now of much moment.

The actual amount of power used for such service is easy to compute. Taking for a unit a train composed of one long motor car and one trail car, capable together of accommodating nearly two hundred people, we can deriv the necessary power. The weight of the two cars complete would be about fifty tons of which about thirty tons would belong to the motor car and twenty to the trailer Allowing for ten tons live load the total weight of the loaded train is sixty tons.

The tractive power per ton may be taken direct from railway practice since the roadbed and rails are, or always should be, the same ordinarily used in steam railroading

For such track and speed the tractive coefficient shoul never be more than 12 lbs. to 15 lbs. per ton. Taking the latter figure as covering all ordinary contingencies of curves etc., the horizontal effort becomes 900 lbs.; to this must be added the air resistance, and whatever resistance may be due to grades. At thirty miles per hour the air resistance is between 3 lbs. and 4 lbs. per square foot of surface normal to the direction of motion.

Allowing 200 lbs. for this factor of the resistance we have a horizontal tractive effort of 1100 lbs. and there would be required at thirty miles per hour the expenditure of eighty-eight mechanical horse power.

Maintaining this speed of thirty miles per hour on grades, the additional horse power required would be ninety-six for each per cent of grade, or dropping the speed to twenty miles per hour on the grades, sixty-four horse power for each per cent of grade.

Allowing about eighty per cent net efficiency from the motor terminals to the wheels it appears that the electrical energy to be delivered to our unit train to maintain a uniform speed of thirty miles per hour is about eighty to eighty-five kilowatts per train on a level track. To maintain a thirty mile per hour schedule under ordinary conditions, including stops and the net effect of such casual grades as might generally be met in suburban work, might require 100 k. w., but the mean daily output per train in service would hardly rise above the original figure of eighty to eighty-five kilowatts.

During crowded hours an extra trailer would often have to be carried. This would add about twenty-five tons to the weight of the trains and would call for about thirty-six additional horse power, bringing the total kilowatts for the train up to nearly 120.

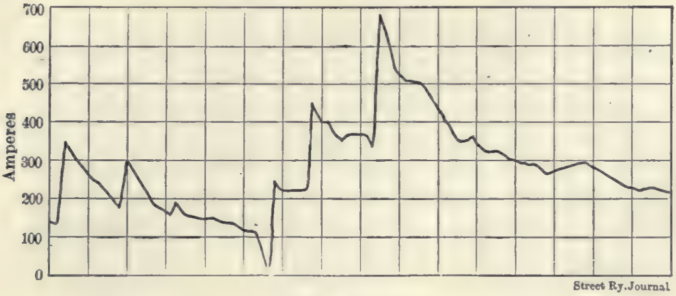


FIG. 124.

This estimate of power, based on known data as to the weights and speed, is fully borne out by experiments on trains in actual operation.

Figs. 124 and 125, give the actual power taken to drive trains of five and three cars over a substantially level track at approximately thirty miles per hour. No continuous records of speed were taken, but the averages were about as stated, sufficiently near for a fair comparison. Fig. 124 is the record of a run with a train consisting of a motor car and four trailers weighing, with a moderate load of passengers, very nearly 122.5 tons, a trifle more than double the weight of our assumed standard train. The average voltage was 530 and the average amperes are very nearly 290, or 154 k. w. Since the air resistance for four cars is but a trifle more than for two, the close agreement of this run with our estimate is obvious.

Fig. 125 shows a run with one motor car and two trailers weighing with the passengers 89.5 tons; speed about the same as in Fig. 124 and average voltage 475. The average current appears to be about 230 amperes, giving 109 k. w. total output, which again, reduced to a two-car, sixty-ton basis gives in the vicinity of eighty kilowatts for the normal train. Another run over the same track as in Fig. 125 with a three-car train two tons lighter, and in the opposite direction showed an average power consumption of 125 k. w. The same motor car was used in all three tests. The sudden increases in the current were mainly due to sudden changes at the controlling apparatus causing rapid acceleration. These very large momentary currents are, of course, undesirable and can be much reduced by careful handling and better adjustment of the controller to its work.

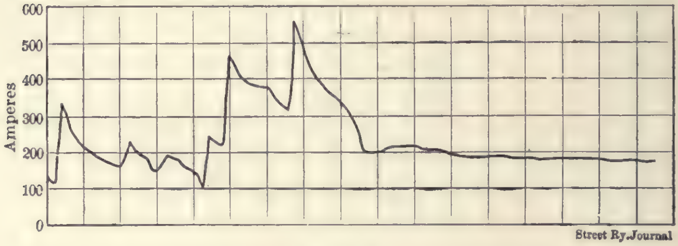


FIG. 125.

The normal average current for such a train at 500 volts would then be not far from 160 amperes. With a working voltage of about 600 at the motors, which is a desirable arrangement, about 135 amperes would be required. One would not go far wrong, then, in taking for ordinary cases 200 amperes as about the largest average which would be called for by any one train, allowing the use of two trailers when convenient. The ordinary loaded train would average 135 to 160 amperes, according to the voltage.

The experience of the past two years on the Nantasket Beach line has added materially to our knowledge of electric railway work of the larger sort. Fig. 126 shows in detail the result of one of the experimental runs over the entire length of the road, 10.5 miles. The train con-

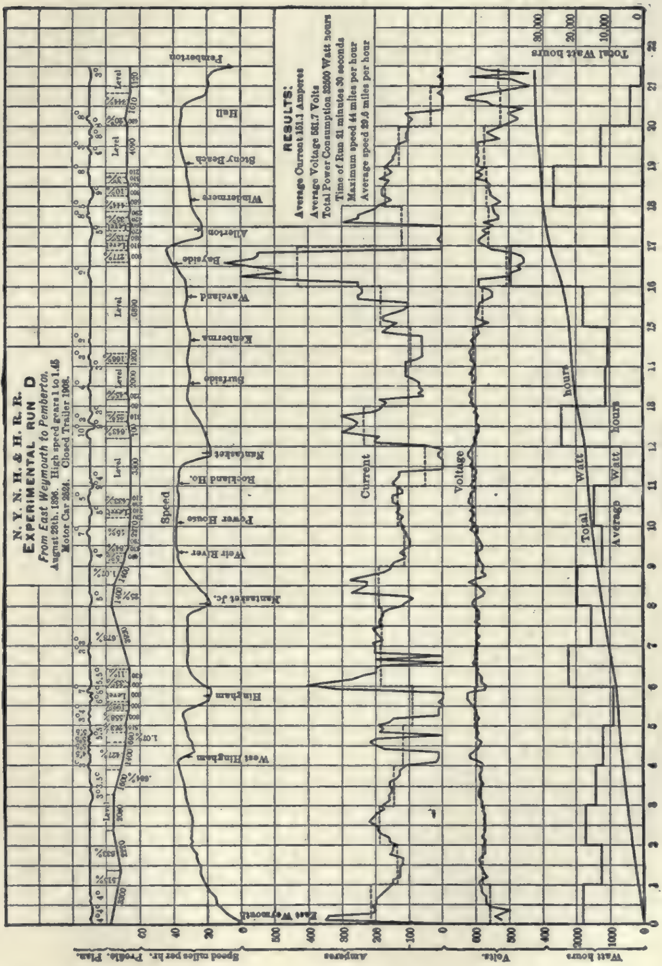


FIG. 126.

sisted of a motor car weighing 32 tons and a trailer weighing 28 tons. Both were mounted on double trucks with 36 in. wheels, and the former was equipped with two 125 h. p. motors, geared, with a speed reduction of 1.45 to 1, to the axles of the same truck. The diagram shows the speed, amperes, volts, watt-hours and time, together with the curves and profile of the road. The power required at an average speed of 29.6 miles per hour was 87.89 k.w. equivalent, taking account of the motor efficiency at this particular output, to about 90 mechanical horse power.

A service run with the same train weighing with its passengers 64 tons, at an average speed of 17 miles per hour, including twelve stops at intermediate stations, required an average output of 65.2 k.w. In this case the severe work of acceleration, due to the numerous stops, is very evident.

In these and many other runs on which careful measurements were made, one singular fact regarding the train resistances was noted, which has an important bearing on railway work.

The output required for a motor car alone was not greatly increased, for the same speed, by the addition of a trailer. Even two or three trailers produced a disproportionately small increase. The apparent decrease of the tonnage coefficient on long trians has been well known in general railway work, but the ease of exact measurements makes it particularly striking in the case in hand. Of course even here the varying conditions of track, load, speed, acceleration and wind produce somewhat divergent results, but the same general fact is apparent throughout.

The apparent power required per ton is much greater for the motor car than for those forming the train. The following table shows the approximate results obtained at several different speeds and under various conditions, in kilowatts per ton.

The reduction for air resistance is made by the data from Fig. 135. The value of this resistance has been so thoroughly determined for these very moderate speeds

SPEED—MILES PER HOUR.				
	14*	17**	30	40
Motor car................	2.8	1.44	2.2	2.0
Motor car less air pressure.	2.5	1.14	1.41	1.0
One trailer...............	0.71	0.55	0.46	0.5
Two trailers..............	0.85		0.66	
Four trailers.............			0.53	

* Heavy acceleration. ** Service run.

that the above results can hardly be materially in error. Even taking into account the uncertainty introduced by the wind and gear friction, the above results, particularly those at low speeds, show clearly enough that we are here dealing with differences of resistance other than those produced by air pressure.

It is altogether probable that the tractive resistance of the driving wheels is materially greater than the pure rolling friction of the other trucks. This is assuredly the case if there is any tendency to slip, and near the limit of adhesion the effect must become very noticeable, which would produce an apparent increase of tonnage coefficient with trains above a certain length and weight. Under even ordinary conditions there must exist a certain grinding friction of the driving wheels, much larger, to judge from the data at hand, than ordinary rolling friction, perhaps twice as great. A similar condition is thought by many engineers to hold with respect to locomotive driving wheels.

The matter is important since it indicates great advantage in employing trains rather than the single cars which have often been advocated for electric service on a large scale.

The Nantasket experiments also afford valuable data with respect to the power required for acceleration. They are fairly concordant and show, for a 60 ton two car train, that acceleration from rest to 25 miles per hour in one minute, requires an aggregate expenditure of just about 2 k. w. h., *i. e.* about 120 k. w. average output.

This gives an experimental basis for computing the power required by a train making frequent stops, as in suburban service on steam railways. We shall calculate a case of this kind later. The important fact to note concerning such service is the very severe acceleration due to the short runs between stations and the high maximum speeds that must be reached. With stops every mile or mile and a half this maximum has to be something like twice the average speed including stops, and can only be maintained for a fraction of a minute, after which the brakes have to be applied. For example, if the stations are a mile and a half apart and the running speed is to be 30 miles per hour, the maximum speed must be 50 to 60 miles per hour and it must be reached in one minute or less. This would, for a 60 ton train, demand during acceleration an average of 250 to 300 k. w. The nearer together the stations the more severe becomes the work of acceleration due to a given schedule of speed. With stations as near together as they have to be in some elevated service the tremendous drawbar pulls are likely to come near to the limit of adhesion if a single motor car be used and there is then considerable to be said in favor of making every car a motor car, in spite of the loss of efficiency. Where certain work must be done as part of the necessary traffic scheme the method that accomplishes it need not be too closely scrutinized. Single cars or trains with many motors quite certainly take considerably more power to drive at speed than ordinary trains of the same capacity and the advisability of using one or the other is purely a question of local traffic conditions. Each case of this kind must stand on its own merits, with the presumption rather in favor of ordinary train practice until it is shown to be inadequate under the conditions imposed. On the other hand if one is compelled to resort to very extreme work of acceleration it is more economical of power to accelerate very quickly and then coast than to accelerate more slowly and cut off current only to put on the brakes.

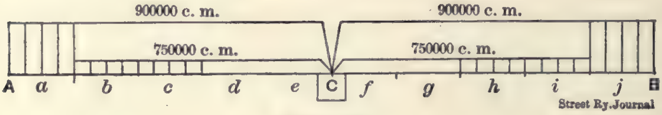
In starting, during certain periods of acceleration and on grades, much more current is required. From Fig. 125 we may judge that the current, even at 600 volts working pressure, might well rise to 400-500 amperes, while to maintain schedule on a grade of, say, two or three per cent would demand fully as much. Altogether the maximum working current per train must be taken as high as 500 amperes, although this amount would be seldom called for.

FIG. 127.

The supply of so great a current to the moving train is not altogether a simple matter, and has involved considerable experimentation.

The ordinary street car trolley burns badly with such currents, and special wheels arranged to secure extra large contact with the trolley wire are needful, while sometimes two independent trolleys have helped the matter.

The trolley wire itself is necessarily of large cross section, so large as to involve some trouble in support, and several unusual shapes have been tried to improve the contact area and facilitate suspension. Fig. 127 shows three such forms, the simpler of which is in use on a portion of the Nantasket Beach electric road, the Cleveland & Lorain Railway and the Boston Subway. Neither shape of the right hand pair is unobjectionable, though both give a good opportunity for gripping the wire firmly in the clamps without forming projections which would be likely to throw off the trolley when running at high speed. Both are likely to give trouble from twisting, so as to make poor contact with the trolley wheel. The more nearly circular the cross section of the wire can be made, while still permitting projections or grooves for gripping, the more smoothly the trolley will run and the better for general contact. A plain round wire would be the best if it could be clamped so as not to produce projections to cause trouble at high speed. A grooved round wire with special clamps has recently been introduced with good results. It appears at the left in Fig. 127. Of the two pioneer heavy service roads, one, the Nantasket, uses the two-lobed trolley wire shown in Fig. 127, weighing one pound per linear foot, the other, the Mt. Holly branch of the Pennsylvania Railroad, took for its rather lighter service a No. 00 plain wire.



Street Ry. Journal

FIG. 128.

To get a clear idea of the power requirements on this class of road let us assume a fairly simple case and work out the feeder system. Let A B (Fig. 128) be a straight suburban system, 50,000 ft. (nearly 10 miles) in length, with no grades steeper than ½ per cent, double tracked throughout with stations, say, every 5000 ft. Let the power station be at C, the middle point, which would generally be as convenient as anywhere. We will assume trains to be run on ten minute's headway, and to make the round trip in an hour. During the busy hours, 7-10 A.M. and 4-7 P.M., the trains should consist of motor car and two trailers, at other times of motor car and a single trailer. Certain trains would probably have to carry three trailers. From 8 P.M. on, and before 7 A.M. twenty minute headway would be sufficient. During the busy hours there would then be twelve trains in service, six of them heavily loaded, and each a three-car train. From the rush hours on the number of trains would be the same as before, until 8 P.M., after which six trains would suffice.

From these data we may calculate the power which would have to be delivered. As in other railway work the feeding system is really determined by the conditions of maximum load. This would usually fall between 8 and 9 A.M. during which period six trains would be in service on each half of the line. Of these the outgoing trains would be nearly empty, but on the other hand all the ingoing trains would be crowded, and one or two of them would carry an extra car. We must, therefore, allow for extra load, and a fair assumption would be to consider all the trains as three-car trains well loaded. This means not far from 120 k. w. per train, about 1440 k. w. for the full output of the station.

The working voltage should be as high as feasible. Without any radical innovations it is quite practicable to allow a normal voltage of 600 at the motors. This should not be much exceeded, while the pressure may without trouble be allowed to fall ten per cent below this at the termini during heavy loads. Let us first examine the terminal conditions. Two trains will ordinarily be handled in that region, requiring by our assumption 240 k. w. To allow for rapid acceleration of a heavy train, fully this amount of power may be temporarily required, but two trains will not have to start together. If, following Fig. 119, we allow 500 amperes available at the terminus we shall be safe so far as this point is concerned.

As to drop, if we take ten per cent as average during the busy hours we shall not go far wrong, allowing twenty per cent at the termini during heavy loads. Even a little more would be safe if occasion demanded, so that if the dynamos gave about 600 volts overcompounded about ten per cent, say, to 670, the minimum pressure could be safely taken down 150 volts to 520. We must then have at the termini enough feeder capacity to give 500 amperes without dropping the voltage below 520.

Now for such a road as we are considering the track should be first class, rails not less than eighty pounds per yard, and most carefully bonded. Four lines of eighty pound rails give an equivalent conductivity of about 5,120,000 c. m. Assuming that the bonding lowers the conductivity one-third, the track is equivalent to about 3,400,000 c. m. of copper. In spite of this the heavy service makes it necessary to take, say, 14 as the track constant.

Now turning to Plate II (p. 81) we can find the feeder area. It is 700,000 c. m. per one hundred amperes for fifty volts drop. In our case then the feeder area is

$$\frac{700,000 \times 5}{3} = 1,166,000.$$

This feeder should supply the terminal sections of track, say, 5000 ft. long. For convenience we may divide the line into 5000 ft. sections lettered on Fig. 122. Sections *a* (and *j*) being thus disposed of, we may turn to sections *b* and *c*, treating them together. The average distance of transmission is 15,000 ft. and the maximum load may be taken as one train under full headway and one starting, say, 650 amperes. From Plate II the copper is

$$\frac{400,000 \times 6.5}{3} = 866,000 \text{ c. m.}$$

Similarly, for sections *d* and *e* we have approximately

$$\frac{140,000 \times 6.5}{3} = 303,000.$$

Now for the working conductors and then to fine down the feeders.

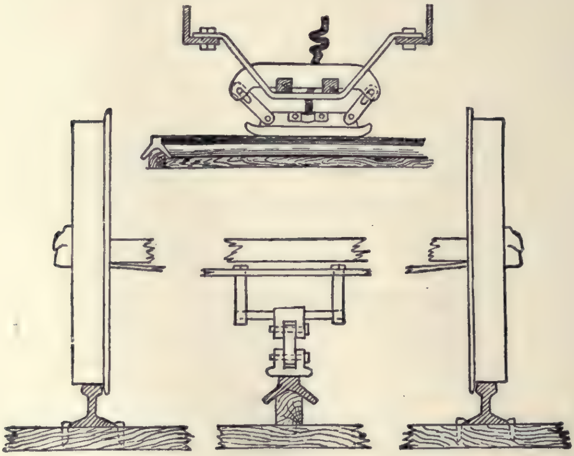
Using trolley wire such as is used on the Nantasket Beach road, we should have about 660,000 c. m. available at once in the two trolley wires. Much smaller trolley wire would be inadvisable on account of lack of contact surface and carrying power. Sections *d* and *e* will obviously take care of themselves and generally have large capacity to spare. Along *b* and *c* the trolley wire is available, and even if the maximum load were at the further end of *b* a 750,000 c. m. feeder extended from *c* along these sections would give sufficient conductivity. Now for the terminal sections. Throughout *a* the 660,000 c. m. of the trolley wires is available. Hence up to the beginning of the section 1,000,000 c. m. is sufficient without allowance for help from the other feeder. Just how much this help would be is hard to estimate. It should certainly not be less than 100,000 c. m. If then the long feeders are of 900,000 c. m., the maximum load conditions for the road as a whole will be properly met. We may now count up the copper as follows:

	Ft.	Lbs.
Trolley wire	100,000	100,000
750,000 c. m.	40,000	90,000
900,000 c. m.	50,000	135,000
	Total	325,000

This copper would cost in round numbers $50,000, and in place, including the pole line, nearly or quite $60,000. At average load during busy hours, say, 1800 amperes total, the loss would not be far from ten per cent, while the average loss for the all-day run would be considerably smaller.

But this is not the last word on the working conductor question by any means. A daring and apparently highly successful experiment has been carried out on a new section of the Nantasket Beach line 3½ miles long, which promises good results on a larger scale. It consists of the application of third rail supply to the service track of a steam railroad. The line thus changed was that section of the Plymouth division of the New York, New Haven & Hartford Railroad, lying between East Weymouth and Nantasket Junction. An insulated steel rail was placed midway between the track rails and made to serve as the working conductor. Current is taken from this rail by means of a soft cast iron shoe carried beneath each of the trucks. The third rail is laid in thirty foot lengths, each supported by four ash blocks, saturated with insulating compound by treatment in vacuum pans. These blocks are so let into the ties that the surface of the third rail is one inch above the track rail. The third rail is bonded with two heavy copper bonds at each joint, and where there are crossings the rail is omitted and the cars pass over on momentum. The rail is made continuous electrically over the crossings by a buried lead covered cable, and a sloping leading-block of hard wood is spiked to the ties at each side of the crossing to prevent shock to the shoes. The arrangement of the third rail and the contact shoe is shown in section by Fig. 129, and an elevation of a single shoe in Fig. 130.

The supply rail weighs ninety-four pounds per yard and is of rather odd shape, to secure sufficient weight without making the rail too high, and to shelter the insulating blocks. The shoes are a little more than one rail length apart, and are supported, as shown in Fig. 130, by a double toggle joint having a rather limited play. The weight of the shoe, about twenty pounds, is enough to give good contact.



FIGS. 129 AND 130.

The return circuit is, of course, through the track rails, which weigh about ninety pounds per yard, and are thoroughly bonded with short lengths of copper cable. As a matter of fact, during some weeks of successful operation the bonding was incomplete, and contact was furnished by the fishplates at many of the joints. The system has now been working several seasons with entire success. The cars, which run over the entire Nantasket Beach road, are, of course, equipped with an overhead trolley as well as with the contact shoes, and from Nantasket Junction to the Pemberton terminus the overhead trolley line is in use. The character of the overhead structure in this part of the line is well shown in Fig. 131. The greater neatness and simplicity of the third rail arrangement is obvious. Until this experiment fear of serious leakage has deterred engineers from using such construction on ordinary road-beds. A regular railroad construction with rails carried on ties slightly above the surface of the ground is very

FIG. 131.

much less liable to leakage than street railway construction with nearly buried rails, particularly since in the former the third rail can be supported on adequate insulators.

Besides this, an amount of leakage which would be formidable in street railway work may be relatively quite small in the heavy service of a suburban line. The third rail has about 700 insulators per mile, and if they are of tolerably good material, the leakage current must necessarily be small even in very wet weather. Tests show that this is so. In ordinary weather the leakage is not serious, and under the worst conditions it still leaves the system in good operative condition. This might be expected, for it is certainly a poor insulator that, even when damp on the surface, would let pass any considerable current under a pressure of 600 volts. If the track is not actually submerged, the insulation should remain fairly high if the insulators do not deteriorate. Snow is a rather good insulator, and if the roadbed is well drained, even melting snow will not cause much inconvenience.

Such a third rail structure generally renders feeders quite needless. For a road such as we have been investigating a one hundred pound supply rail on each track would give, when well bonded, a total equivalent conductivity of just about 2,130,000 c.m., allowing one-third of the total resistance to be in the bonding. This is almost precisely the equivalent of the available copper shown in Fig. 128. On a longer road, or with heavier service, supplementary feeders would be necessary.

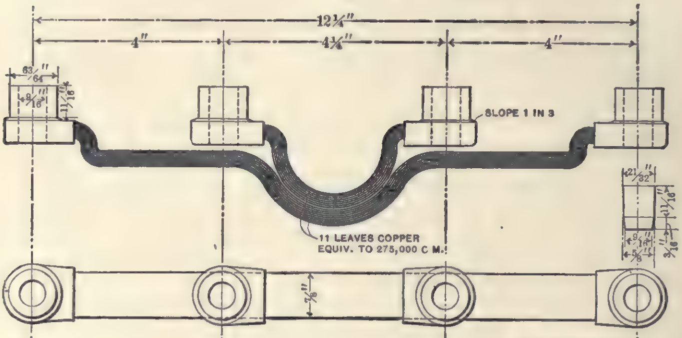
The cost of this third rail system is decidedly low. A one-hundred pound rail weighs eighty-eight tons per mile, costing at present prices not far from $2300. Insulators, placing and bonding should not exceed $700 per mile additional. On this basis the third rail system can be installed rather more cheaply than the overhead system and is far simpler to maintain and operate.

A sectionalized third rail has been more than once suggested as a remedy for leakage. Whatever may be its merits for street work, it is disadvantageous in that it virtually throws away the immense conductivity of the supply rail and thus greatly increases the first cost of the line. A fraction of the extra expense applied to careful drainage of the roadbed and good insulation would render sectionalization needless for this particular kind of work.

A copper third rail deserves consideration in connection with this class of work on account of its great convenience in the matter of insulation, ease of placing, and elimination of the bonding difficulty. Its net cost is rather more than that of a steel third rail.

The third rail section of the Nantasket line has now been installed about three years and although it has not been in operation during the winter, when the most trying weather conditions would have been encountered, the results have on the whole been so satisfactory that the railway company has equipped another of its lines in a singular manner. This is a line extending from Hartford to Berlin, Conn., via New Britain, a distance of 12.3 miles.

The arrangement of the conducting rail is substantially that shown in Fig. 130. The lower edges of the rail are little more than 1¼ in. above the ties and the road is operated throughout the winter thus furnishing a crucial test of the insulation. Since the construction of this Hartford-New Britain line it has been extended beyond New Britain to Bristol a distance of 8.8 miles and between New Britain and Berlin 2.5 miles. The Nantasket Beach road has also been extended from East Weymouth to Braintree 4.4 miles. These additions after a year or two of experience are strong evidence of the operative qualities of the third rail system, which is used throughout. Still another branch line of the N. Y., N. H. & H. R. R. has been transmuted into an electric road with others to follow. The branch referred to is that from Stamford to New Canaan, Conn., 8 miles long. Here the overhead trolley is used to facilitate exchange of traffic with the Stamford street railway if convenient. The trolley wire is No. 000 and No. 0000 and there has been no trouble in getting adequate contact. The bonding on this and similar lines is worth noting as it seems to be especially good. At each joint are applied a pair of "Crown" bonds of the general type shown in Chap. II. both of leaf copper proportioned and arranged as shown in Fig. 132. This bonding is applied under the base of the rails, the terminals being forced upwards into holes drilled in the base and the drift pins being squeezed up into place by a special tool.



Street Ry. Journal

FIG. 132.

The countersunk bond terminals are then set up with a hammer so that the pins cannot work loose.

Another ingenious innovation in this road is found in the motor trucks. Each of these is fitted with two 175 h. p. motors which are carried by and suspended to a truck frame independent of the car truck proper which rests upon it at the boxes. Thus the whole upper part of the truck is removable leaving the working parts freely accessible.

The wooden insulating blocks used at Nantasket have been, so far, fairly successful and have kept the leakage, under ordinary conditions, down to a rather small amount. The insulators, however, have in some cases shown marked deterioration and it is the writer's belief that the leakage will become serious if the use of wood is long continued. Insulators so short and presenting so great surface as these should be of porcelain if they are to have and maintain insulating properties such as the conditions demand.

On these lines it was necessary to keep the third rail close to the ties in order to avoid striking the fireboxes of locomotives occasionally used on the same tracks, but this proximity is certain to produce some disagreeable results unless insulation is more carefully carried out than it is at present.

Moreover the third rail is in no way protected from accidental contact of any kind, and while the voltage employed, 600 to 700 volts, cannot be condemned as highly dangerous to life it is yet certainly beyond the danger line, and can unquestionably produce grave shocks and death. At least one man has been killed on these circuits and others have been injured. It is not putting the facts too strongly to say that to continue the use of an unguarded third rail on surface roads approaches criminal negligence. Aside from this question of danger short circuits are very easily produced on an unguarded third rail and consideration of public safety and private convenience alike demand the suppression of so dangerous a practice.

The facts regarding the leakage encountered on these third rail systems have never been made public. That there is at times heavy leakage admits of little doubt, but the roads have continued operative under rather trying conditions in spite of it. The insulation used seems, however, inadequate and should be assiduously shunned in future work along this line.

Nevertheless we have in the third rail system a very important addition to the methods of electrical traction, and one that is capable of being developed far beyond any point which has yet been attained. The use of proper insulators and the allowance of sufficient clearance under the third rail will lead to greatly improved results, and in the last resort careful construction and drainage of the roadbed will prove immensely helpful.

When the method has been thoroughly worked out it promises to be of very great value in many cases of heavy traction, for it is cheap, simple, easy to apply and gives what most other systems conspicuously lack, an adequate contact area on the working conductor. The greatest difficulties yet apparent in the third rail working are the troubles due to sleet and to failure of the bonding. In sleet and ice a coating of the rails is supplied that is, so far, almost impossible to cut through enough to get good contact, and under these circumstances the third rail lines are sometimes driven back to steam locomotives. It should not be impossible to devise means of cutting through the sleet successfully, but thus far the difficulty has been formidable.

Even the thorough system of bonding employed gives considerable trouble from the gradual breaking of bonds under the stress of continual shocks at the joints. The center third rail is particularly bad in this respect, as it takes up the space in the middle of the track so as to make proper surfacing and tamping of the roadbed extremely difficult. A side third rail would be far easier to keep up in this respect. As to bonds the writer is inclined to think that very flexible cable bonds with the terminals electrically welded to the rail would give relief from the present situation. At all events it is well worth trying.

One of the standard open cars of the Nantasket Beach line is shown in Fig. 133. Each has sixteen seats and will accommodate fully one hundred passengers. Sixteen of these are fitted up as motor cars and similar cars are used as trailers. Each motor car is fitted with two G. E. 2000 motors of the type shown in Fig. 134 arranged for series-parallel control. The cars are fitted with air brakes and air whistle, the air being pumped into a tank by a motor automatically controlled by the pressure. The motors are good for over a hundred horse power each at full field, and on the straight level stretch in the middle of the Nantasket Beach line a speed of more than seventy miles per hour has been reached. At such a speed the motion is quite smooth and the great speed cannot be realized except by timing the car. The normal speed is from twenty to thirty miles per hour in regular service, and the system has proved entirely reliable.

For this heavy special or suburban service electric power is singularly well suited. It does the work well, at high efficiency and at moderate cost. Basing an estimate of cost on a normal two-car train, requiring eighty kilowatts while running and allowing for this eighty kilowatts average output at the station, we can figure readily the cost of power per train mile. The train makes an average of about twenty miles per hour. It thus demands four kilowatt hours per train mile. The service is twenty hours per day, and the average load fairly high, probably more than half the maximum. On this basis the power per train mile should not cost, delivered on the line at the station, more than six cents, including station charges of every sort and kind. Two cents additional should cover all charges for the delivery of the power, including the motors. Even

FIG. 133.

more unfavorable conditions than those assumed would generally leave the power charge per train mile at not over ten cents. This is, of course, relatively very much better than street railway practice, but the units are far larger, the service easier in every way, the grades smaller and the work far more controllable and regular.

By far the most interesting line of advance in electric railway work is toward long distances at very high speeds. The idea of clipping the wings of Time by doubling our present railway speeds is a very attractive one, not lightly to be cast aside as chimerical.

The problem naturally divides itself into three queries: Can it be done? How can it be done? Will it pay? As regards the first question we are now in a position to give a definitely affirmative answer. Suppose we set for our goal a schedule speed of one hundred miles per hour. Under the conditions which may be expected to obtain with express service, the corresponding maximum speed would not have to be very high, probably not over 120 miles per hour.

FIG. 134.

Obviously the attainment of such speed depends on only two things—the delivery of sufficient power to the moving locomotive, and the mechanical security of track and rolling stock. In our present express service both here and abroad trains have within the past few years repeatedly run on nearly level track at the rate of one hundred miles per hour and its immediate neighborhood. This speed has not been maintained for more than a few miles at a time, but it has been accompanied by no special phenomena in the way of vibration, strain on track and rolling stock or rapid increase of resistances. In fact the motion at these high speeds seems to be smooth and the track resistances, if anything, are less than at more moderate speeds. Air resistance, once much dreaded, is not very serious, for indicator cards from locomotives drawing trains at ninety miles per hour or thereabouts show a total tractive effort so low (even below ten pounds per ton in some cases) as to leave very little room for atmospheric resistance.

Perhaps the easiest way to appreciate the facts is to calculate from the best attainable data the power required to drive a given train at one hundred miles per hour. We shall have to exterpolate with respect to some of our data, but so short a distance as to involve very little uncertainty.

The normal resistances encountered by a moving train may be roughly classified as friction, grades and air resistance. The first mentioned, including all the ordinary tractive resistances, is usually ten or twelve pounds per ton of moving weight on good track. Anything below ten pounds is unusually good and few railway engineers would care to count on anything below eight pounds even under the most favorable circumstances, although lower results are probably now and then reached at high speeds.

The atmospheric resistance used to be taken as varying with the square of the speed, but the work of Crosby and recent experiments with fast running trains have made it certain that up to speeds of fully 125 miles per hour the air resistance increases very little faster than the speed. Moreover it can be greatly lessened by shaping the front of the locomotive into a plane or parabolic wedge. Fig. 135 shows the results of Crosby's experiments with whirling bodies in addition to several points approximately established by direct experiments on moving trains. The latter are somewhat uncertain owing to insufficient data concerning exposed surfaces, but the results given have been taken as large as the data permit, so that they are over rather than under the real resistances.

The data for actual train resistances are in a very badly mixed state. A considerable number of formulæ have been deduced from experiments, but as a rule they have not held far outside the experimental limits. Much of the confusion has arisen from trying to take account of several complex variables in one simple formula. As just noted, the air resistance was at first assumed to vary as the square of the speed and the first efforts at formulae assumed a constant tractive resistance plus a term including the square of the speed. Now the law of squares assumes in general terms that at double speed, double the number of cubic feet of air are displaced per minute and at double velocity. Now an elastic fluid like air, pushed at a speed far below its velocity for compressional waves, obeys no such simple law. Experiments with projectiles show that the variation of resistance with the velocity of the disturbing body changes enormously with that velocity. Of all the early workers Rankine alone

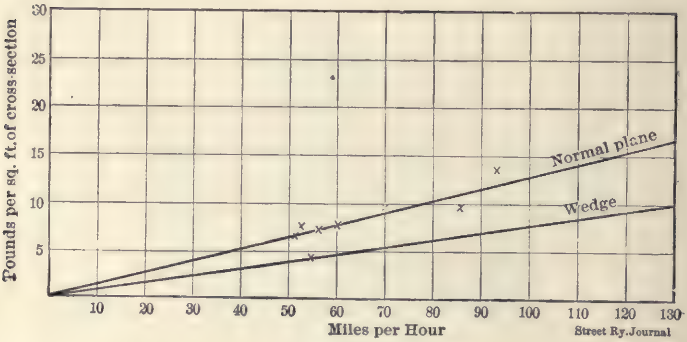


FIG. 135.

assumed a term in the first power of the speed only, qualifying it by the assumption that each ton of engine should be reckoned as two tons in computing the weight of the train. A linear formula substantially takes it for granted that doubling the speed doubles the air displaced per minute, but leaves the velocity of displacement unchanged, or that both quantities are by no means doubled, which is probably nearer the truth. Crosby's experiments make it perfectly clear that, at least for bodies no more than one or two diameters long, the air resistance is certainly very close to a linear function of the velocity, and very far from being a function of the second power. For elongated rough bodies moving endwise, such as trains, Crosby's values are probably somewhat low. Not only are there powerful air eddies at the rear if it be blunt, but there are, as an experimental fact, strong inward swirls dragging against the train.

In general, formulae based on the second power of the speed give resistance values at high speeds much greater than are actually found, while those based on the first power give two little resistance at very low speeds. Those including both powers are more or less successful compromises according to the data.

Broadly speaking the facts seem to be about as follows: 1. Tractive resistances, i.e. journal and track frictions considered as a whole, tend to fall off at very high speeds very possibly showing a weak maximum at some moderate speed. 2. Air resistance is nearly a linear function of the speed, with a slight tendency to rise. The combination of the two obviously leads to a shape which can be approximated by either a parabolic or hyperbolic function of the speed in either case of small curvature within the range taken. At high speeds either function approximates to a straight line; while at low speeds the curvature is more manifest.

At the speeds with which we wish here to deal the best available formulae, i.e. those best confirmed by experiments at very high speeds, are those of Mr. Angus

Sinclair, Mr. David Barnes and Mr. Vauclain, which are respectively

$$R = 2 + .24\ V$$
$$R = 4 + .16\ V$$
$$R = 3 + .166\ V$$

In which R is the total train resistance per short ton and V the speed in miles per hour. They are intended for use between 40 and 75 m. p. h.

Fig. 136 shows these equations graphically and with them a linear function based on Crosby's air resistances and an assumed uniform tractive resistance of 8 lbs. per ton at these high speeds, with the equivalent of 100 sq. ft. of normally exposed head surface. This is large enough to take account of eddies and lateral air resistance. All these formulae are for running in still air, and none of them are based on any exact theory of resistances, but merely fit closely the facts around which they have been built.

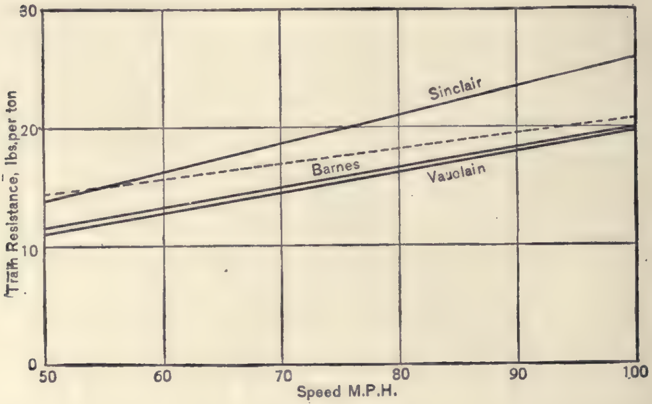


FIG. 136.

It should be distinctly understood that these formulae apply to trains of moderate length and not to single motor cars such as have been used on electric railways.

The different values of the first term in the various formulae indicate the uncertainty as to the real values of the various forms of track resistances. If, as the writer believes, the sum of these gradually rises and then falls off at very nigh speed, a reason would appear for the apparent rapid rise of total resistance at medium speeds which furnished a basis for the large terms in V^2 in the earlier formulae derived for experiments at moderate speeds. All the experiments at 60 miles per hour and upwards show that if there be a term in V^2 its coefficient is very small. It is, of course, possible that the total air resistance including eddy effects passes through a maximum, or one of a series of maxima as does the resistance of a ship, but only towing a train by a very long cable is likely to bring out the real facts of the case.

For computing this and for estimating power at very high speeds it is best to recognize squarely the fact that one is dealing with two distinct classes of resistance, one depending on the weight of car or train and the other on head area, both being more or less mixed up with the length and number of cars. The process of calculation is by no means difficult and is probably more accurate than any moderately simple formulae. In all such calculations for high speed work it must be borne in mind that all the facts concerning resistances point to the use of a train rather than to a single car, driven by two or four large motors instead of more smaller ones.

From these data we can calculate the power required to drive a given train at, say one hundred miles per hour. We will assume a three-car train, motor car and two regular coaches, weighing complete with passengers 140 tons. This demands no special construction; in fact the less departure from the usual form and appearance of cars the better with respect to securing traffic.

It is worth while, however, to give the locomotive a head in the form of a parabolic wedge, which is slightly better than the wedge of Fig. 135, to vestibule the cars snugly, and to build the cars as free from projections as is consistent with usual models.

With these precautions the total equivalent sectional area could easily be kept within 100 sq. ft. Nearly all of this, too, can gain advantage from shaping. For the relative resistance of wedge and plane Fig. 135 gives accurate values, while the close agreement of the experiments based on normal surface attests their general accuracy. Adding one-third to the wedge value for 100 miles per hour to take account of plane and irregular surfaces, we have a total atmospheric resistance of ten pounds per square foot.

The track resistance we will assume at eight pounds per ton since this value is quite attainable at high speed on a good track, and furthermore was used in computing the points shown on Fig. 135 so that if eight pounds is too low, the air resistances are too high. We may now compute the total train resistance as follows:

140 tons at 8 lbs., 1120 lbs.
100 sq. ft. at 10 lbs., 1000 lbs.

Total drawbar pull, 2120 lbs.

At 100 miles per hour, 8800 ft. per minute, this means 565 mechanical horse power developed by the motors. This power would be raised to about 1300 h. p. in taking a one per cent grade at the same speed. At 125 miles per hour, the assumed maximum, the air resistance would rise to about thirteen pounds per square foot and the horse power to 733. Even if through increased speed and headwind the air resistance were doubled, the necessary output would still be below 1000 h. p. We may safely assume that with a nearly level track, 1000 h. p. would suffice for all service conditions, while the normal output would be between 500 h. p. and 600 h. p.

Now this output can readily be reached with a powerful locomotive, and except for the difficulties of firing, the speed mentioned could be maintained by a locomotive with a single car. The advantage of electricity lies with the removal of this difficulty and decrease of useless weight, together with what advantage can be gained from a very large and perfeet power plant. That such an output can easily be reached by motors on the motor car admits of no question, since it has already been done by the Baltimore & Ohio tunnel locomotives under more trying conditions, i. e., moderate speed and enormously heavier trains, thus robbing the motors of the advantage of high rotative speed.

As regards track, the best is required and the curves should be very moderate, not less, perhaps, than 2000 ft. radius. But the speeds in question are quite feasible on a well laid and well ballasted track. Dr. P. H. Dudley, probably the greatest living authority on track, designed several years ago a 105 lb. rail section which he considered would give a perfectly safe track for speeds as high as 120 miles per hour, and his dynagraph records show, moreover, that for such a track there is a marked saving in power owing to much smaller deflections of the rails. A 140 ton electric train would give much less strain on the track than is now found in the case of fast express trains of approximately double that weight.

Nor is the driving wheel speed dangerously high. With good steel wheels the assumed speed would have to be doubled before the factor of safety would be seriously reduced.

Altogether, the evidence shows that a schedule speed of one hundred miles per hour is quite possible without calling for extraordinary power, unusual material of construction or great innovations of any kind.

As to methods, divers are available. Ordinary continuous current motors worked at, say, 1000 to 1500 volts are competent to do the work, but to facilitate distribution and keep down the working current, alternating motors are desirable, monophase preferred if practicable. With polyphase motors the work is not now difficult. The synchronous motor with special means for starting is the neatest if stops are very few, but is impracticable for heavy work of acceleration. For the high rotative speed required it is not difficult to design induction motors with both high power factor and great efficiency, amply capable of doing the work and doing it well. Probably such motors offer on the whole the best available means for attaining the end in view. Four motors of 150 nominal horse power each, capable of working up to 250 h. p. without much drop in speed would be fully equal to the work, and such motors can be readily produced at any time, as the size is nothing unusual, and the conditions quite easy to meet. The working voltage should, of course, be kept high; 2500 volts is entirely practical, and this pressure would keep the current through the trolley contacts down to limits already passed in present practice. It is at least an open question whether under the conditions which would be found on a high speed road of this kind it would not be feasible and advisable to use the whole voltage of transmission—10,000 volts or more—on the trolley wire and carry the transformers upon the locomotive. A bare wire would be used for the transmission in any event and there is no conclusive reason why it should not be carried over the track. Otherwise a large number of large transformers, aggregating several times the capacity of the motors, would have to be distributed along the line. Unless the service is very heavy this is needlessly expensive and increases the items of labor and depreciation. Except for the added weight and complication a rotary transformer on the car, with continuous current motors, would prove a very practicable method, as has been more than once suggested.

Of course, it might be desirable to use two motors instead of four and to vary the arrangement of parts in many ways, but such details have no place here, where merely the general scheme is under discussion.

The problem of effective braking is a serious one, but not so serious as at first appears. A well protected clear right of way with no grade crossings is absolutely necessary for speeds like those considered, and ought to be insisted on even for present express speeds. With such a clear track and reduced speed, really running on momentum, in nearing termini, the braking effort required is by no means out of reach. The momentum of a 140 ton train at 100 miles per hour is less than that of a 300 ton train at 60 miles per hour and about the same as that of a 300 ton train at 50 miles per hour, and such trains are within the limits of present practice. To be sure, the number of wheels subject to braking would be much less in the electric train, but on the other hand a powerful braking action can be obtained by throwing the motors into action as dynamos through a resistance.

It is not difficult to figure the braking action. Assuming, from one hundred miles per hour to rest, a coefficient of friction of 0.1 between brake shoe and wheels, and a brake pressure of 5000 lbs. per wheel, we have for twenty wheels, eight on motor car and twelve on trail car, a net average retarding effort of $0.1 \times 5000 \times 20 = 10,000$ lbs.

The air resistance would average from our previous computation 500 lbs., and at least 2000 lbs. could be counted on from the motors. The total retarding force would then be $10,000 + 500 + 2000$ lbs. $= 12,500$ lbs. The momentum of the train at one hundred miles per hour would be absorbed by this retardation in about 2500 yds.

As a matter of fact 140 tons is needlessly heavy for a two-car train, and eventually high speed structures would be built much lighter than this. It is, however, perfectly possible to get the speed without departing from ordinary railway construction and the average man at present prefers this to being enclosed in the species of sheet steel projectile that has been thought necessary in many projects for high speed service.

We may now take up the line question. The simplest method is to make the working conductor the transmission line, as previously suggested. For the working conditions, monophase transmission gives quite as great economy as polyphase, for the immense conductivity of the track gives nearly the equivalent of a perfectly grounded circuit. This statement holds approximately even if the conductivity is taken for alternating currents. The cross section of a pair of 100 lb. rails is, roughly, 20 sq. ins. which leaves an ample margin even with the necessary reduction.

Let us assume a line one hundred miles long connecting two cities, and six trains in regular service. Using transformers on the motor cars the whole transmission problem works out in a singularly simple manner. Using 12 as our track constant and taking 10,000 volts as terminal voltage with 2000 volts extreme drop, a single power station in the middle of the line would do the work very easily. Applying our usual formula for 1000 k. w. delivered

$$\text{c. m.} = \frac{12 \times 100 \times 265,000}{2000} = 159,000.$$

Hence a No. 000 wire over each track would do the work easily with not more than 7½ per cent average drop. The total amount of copper would then be about 270 tons, costing, say, $75,000. The transformer capacity should be at a maximum about 1000 k. w. per train, normally not over 800 k. w. This would add a weight of not over eight to ten tons, which can easily be spared from the 140 allowed for.

The copper for a polyphase system would probably be in excess of that just figured, but would not vary materially for the purpose in hand.

If the distribution were effected by delivering power to transformers along the line the cost of the conducting system would evidently be much increased, for the primary feeding line could not be decreased while retaining the same loss and the secondary working line would have to be of at least the same size to carry the necessary working current. For the same total loss the cost of copper would be more than doubled, and the transformer capacity when distributed along the line would also have to be nearly or quite doubled. In point of total cost there is no comparison between the systems, and it is likely that the maintenance of the former would also be considerably less, thus giving a double advantage. Speaking broadly, one may at the present time say with certainty, that a maintained speed of one hundred miles per hour is perfectly feasible as a matter of engineering. It requires no methods that are really untried, no apparatus that could not now be furnished by more than one manufacturer and no precautions that have not already been taken in the best steam railway practice. When there is a demand for such speed, that demand can be promptly met, be it for a road 100 or 1000 miles long.

Increased length would simply mean a power station every hundred miles or so.

Now as to the financial side of such an undertaking. It has been very judiciously pointed out by Dr. Louis Duncan in dealing with the general question of utilizing electricity upon railroads that no existing road having less than four tracks could well undertake to operate an electric express system, since two tracks must be reserved for local and freight service. While a local electric service and express service might be worked on two tracks the general traffic of a system would require more accommodation. The time is not yet ripe for accomplishing all railway service electrically, although there are forerunning shadows of such a probability.

For special high speed service, however, there is ample opportunity now. A road between two considerable centres of population with a schedule speed of one hundred miles per hour, would in a very short time either drive competing roads out of the through traffic or force them to the same methods. The longer the distance the more deadly would be the competition of fast service. Such speed would gather to itself much of the traffic if the termini were but a hundred miles apart, but on a run like that between New York and Chicago it would almost monopolize it.

In any given case the probability of financial success would turn on the amount of passenger and express traffic between the points concerned. The mere motive power expense of the high speed is not serious, nor are the items of repair and depreciation greatly to be feared.

Assuming an average output per train of 600 to 650 k. w. and a cost of power at the station of about 1.25 cents per kilowatt hour, which should be quite attainable in a station of 4000 to 5000 k. w. capacity, the energy itself should not cost above eight cents per train mile including all station charges. Repairs and depreciation on line, motors and rolling stock, and labor on trains should not more than double this figure, so that fifteen to sixteen cents per train mile should cover the regular charges aside from administrative expense. As regards cost of roadbed, it varies so with conditions as to amount of grading, number of crossings, cost of labor and so forth, as to defy close estimation. The rails should not be lighter than ninety to one hundred pounds per yard, preferably the latter, and would cost $10,000 to $12,000 per mile of double track. The overhead electric structure, including the copper for high tension current and the track connections, should not cost more than $3000 per mile. The station complete with steam plant and all necessary electrical apparatus could be installed ready for running for $350,000 to $400,000, perhaps less, for one hundred miles of road. The total cost would thus be for such a section probably not over $15,000 per mile, *plus* right of way and general construction of roadbed, etc.

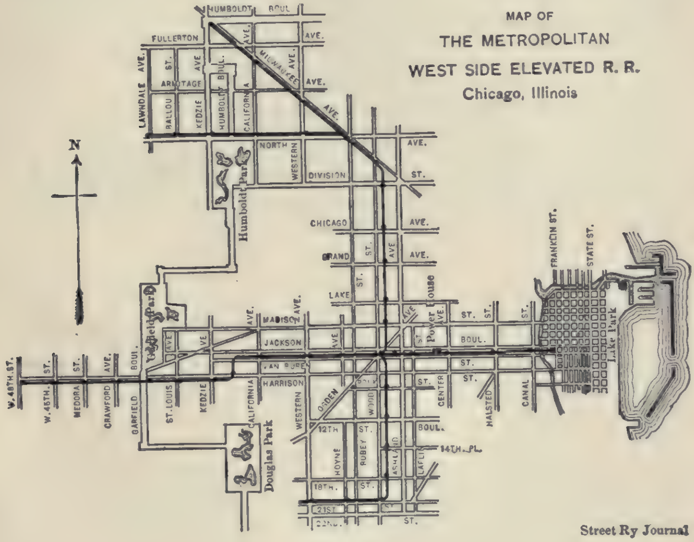
The total cost would thus be not much in excess of that of a first class steam road in the same situation, and with the volume of first class passenger, mail, special freight and express service to be expected between two important termini, it would nearly always pay *if built for cash and operated for profit.*

For elevated roads electric traction cannot be in the future treated as a luxury, but it must be considered a necessity. Even were it notably more costly than traction by steam locomotives, instead of the reverse, public opinion from now on will compel its use in every new enterprise, and on existing roads will make abolition of the locomotive the price of the slightest municipal concession.

Aside from this consideration the experience with the

Intramural line during the World's Fair, and subsequent results on the Metropolitan & Lake Street elevated roads in Chicago and several others, have shown, what theoretical investigation had indicated, that for such service electric power is the cheapest available means of propulsion.

Elevated service is of a rather trying nature on account of the frequent stops—generally about every quarter of a mile—and the large amount of power that has to be used in acceleration. The experiments of Mr. Sprague made on the Third Avenue elevated road in New York established the facts very clearly. It was found that for the ordinary train, weighing from eighty to ninety tons, with a speed reaching, between stations, twenty to twenty-five miles per hour, the average indicated horse power of the locomotives during service was 70.3 reaching an occasional maximum of 185. These great inequalities almost vanished when the whole power for the line was considered. Sixty-three trains were in ordinary use and the mean power, smoothed out by the large number of units, varied little from 4500 in-



Street Ry Journal

FIG. 137.

dicated horse power. The coal used on the locomotives amounted to 6.2 lbs. per horse power hour while in use.

With these facts as to power required the electrical conditions are easy to find. The motors should together be able to work readily up to 200 h.p. with a good efficiency at half this output. The average power required is not far from that already computed for the case of suburban service at higher speed and with rather lighter trains.

The load, however, is on the whole more uniform on the elevated line, although varying more as regards individual units. The cost of power should therefore be somewhat less.

The first notable electric elevated road in service in this country was the Metropolitan line in Chicago. This road, which went into operation in the spring of 1895, was designed to furnish rapid transit on the west side of Chicago. Its general location is well shown on the map (Fig. 137).

The portion now in operation consists of 13½ miles of double track with thirty-two stations. The structure is a substantial one of deep plate girders, admirable mechanically, but very unsightly. The track is of ninety pound rail with massive guard timbers.

The electrical equipment, with which only we are here concerned, involved divers excellent and novel features. In the first place the track rails are not bonded together in the usual way, but each rail is bonded in the middle to the supporting structure, thus giving an enormous iron conductor for the return circuit. If thoroughly carried out this arrangement is exceedingly effective, although it would be well to bond the track itself as a precaution against bad bonds in occasional rails.

The working current is taken from a contact rail located a few inches outside of and above the track rail. This contact rail is supported about every six feet by blocks of paraffine-soaked wood to which it is secured by clips held in place by wood screws. This rail weighs forty-five pounds per yard and the insulated blocks are six inches square and rest upon iron brackets about one inch high, thus raising the contact rail about seven inches above the general level of the track rails.

A rail joint in position is shown in Fig. 138. At the joint the rails are held in line by a light fishplate secured by two bolts, and are thoroughly bonded. The bonds are formed of flexible copper strip about $\frac{3}{16}$ in. thick and the full width of the foot of the rail, under which they are placed and to which they are secured by two large rivets, one on each side of the web of each rail.

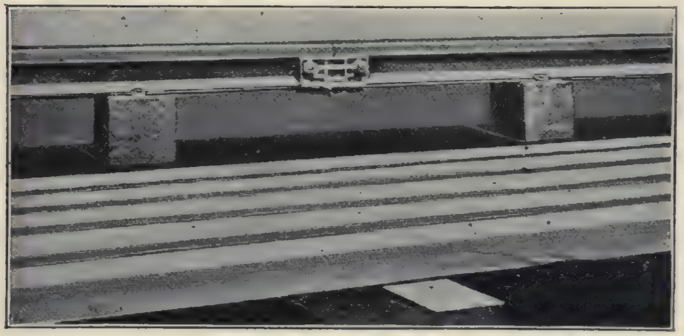


FIG. 138.

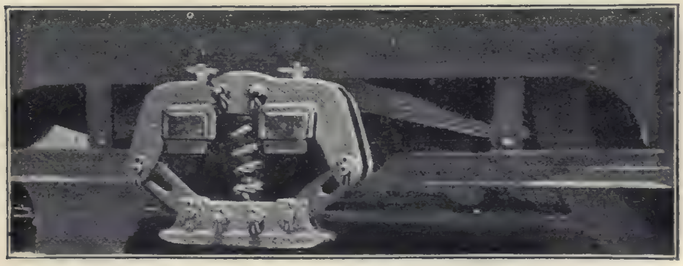


FIG. 139.

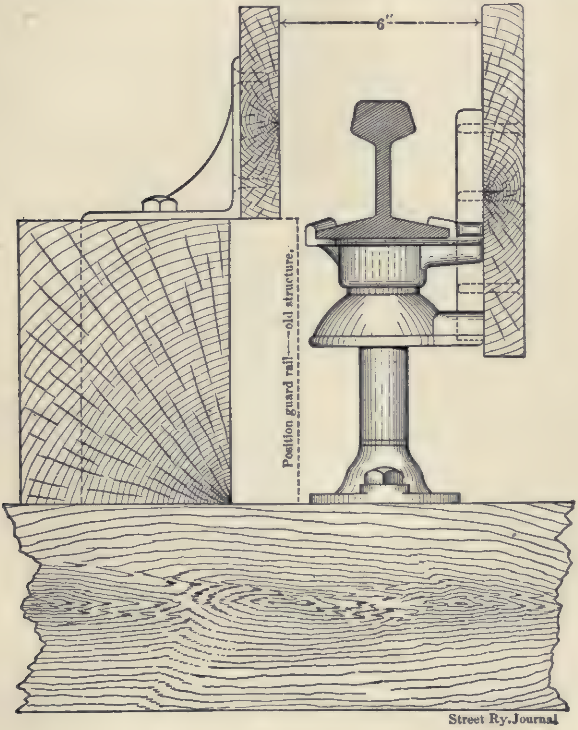
Current is taken off this contact rail by chilled cast iron shoes carried on the trucks. One of these is shown in Fig. 139, which exhibits the arrangement of its parts and the connecting cable. The general construction is that of a double toggle, and the weight of the shoe is sufficient to ensure contact, no spring being employed. There are four of these contact shoes on each motor car, one at each corner. All are ready for service. Two are normally in contact with the feed rail, and when, as at some switches, it is desirable for this rail to change sides, the corresponding shoes go into service. The device works admirably.

The feeding system is extraordinary. It is composed of forty-five pound steel rails, like the contact rail, supported on and insulated from the main structure and boxed with boards to keep them out of mischief. These rails are thoroughly bonded, cross bonded when feasible, and are connected to the supply rail about every 300 ft., oftener at switches and sidings.

On the section from the power house to the eastern terminus, about 1¼ miles, the contact rails alone are sufficient, but westward from the power house run eighteen feeder rails, supplying various sections of the road, and each connected to the distribution board in the power house. On the eastern section current is taken under the Chicago River by lead covered cables laid in a trench dredged in the mud bottom. There are eighteen of these cables, four of 500,000 c. m. each, the others of 235,000. c. m.

The motor cars are forty-eight feet long and, except for a steel sub-frame for extra strength, display no remarkable peculiarities. Each is equipped with two G. E. 2000 motors, like those shown in connection with the Nantasket road. At each end of the car, occupying half its width and projecting into the car and onto the platform, is a little cab containing the controlling apparatus, automatic motor pump for the air brakes, and other accessories. The motor car complete weighs about twenty-five tons. The operation of the whole system has been highly successful.

The Lake Street elevated road, equipped about a year later, shows some useful modifications, although the general equipment is much the same. The working conductor is here a forty-eight pound T rail, located much as in the Metropolitan line, but supported on special insulators instead of wooden blocks. These insulators have a cast iron base and clamping top, united by a bolt sheathed like a



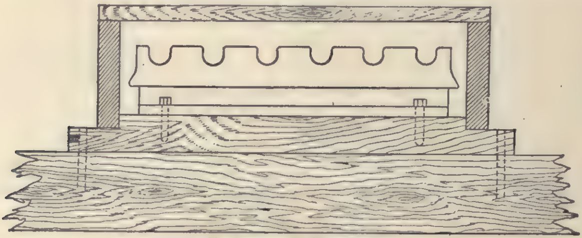
Street Ry. Journal

FIG. 140.

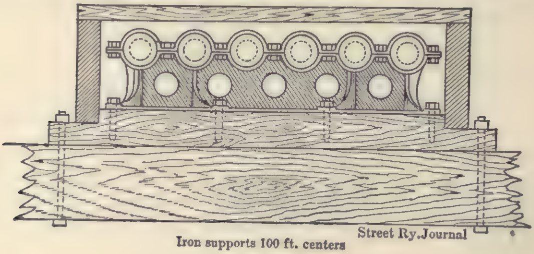
trolley hanger in dense insulation. This bolt is screwed into the base and secured to the cap by a coarse thread cast in cap and insulation and packed with melted sulphur. Fig. 140 shows the arrangement of this standard with its rail and guard planks. These insulating chairs support the rail every six feet. The bonding of the third rail is with copper strips, secured to the rail with two rivets, ¾ in. in diameter, while the track rails are bonded to the main structure at their middle points.

The feeders on this road are of copper cable, bare on the structure, but boxed over. They are supported every ten feet by vitrified clay insulators arranged as shown in Fig. 141. Every hundred feet this clay insulator is replaced by an iron clamp provided with insulating bushing. The cables are of 1,000,000 and 1,500,000 c. m. section.

The contact rail is well guarded in this construction, a precaution that should be carried out on every such road and particularly when a contact rail is used as at Nantasket for a surface road. The earliest elevated road in Chicago, the so-called "Alley" line has been equipped for electric traction and the New York elevated roads are now taking a similar step.



Clay supports 10 ft. centers



Iron supports 100 ft. centers

Street Ry.Journal

FIG. 141.

It is highly probable that copper feeders are in the long run more economical than feeders composed of rails. When freshly bonded the rail feeders just described had about one-tenth the net conductivity of the same weight of copper. At present prices of new rails and copper the total cost of the feeding system is about the same by either method, with the maintenance and depreciation greatly in favor of the copper. Even if old worn out rails were utilized for the feeders it is an open question whether the extra maintenance would not eventually more than eat up the saving in first cost over copper.

Personally the author believes the centre rail construction used at Nantasket to be better than any side rail for elevated service, where it can readily be given ample insulation for all ordinary cases. It is quite as easy to put in place, and the great cross section of the rail is advantageous, since the bonding must be maintained in any case and the extra conductivity costs less than if it were secured by copper feeders.

Whatever the construction, a third rail supply system must be protected against danger of accidental contacts, and the insulators must be kept free of conducting material —brake shoe dust and the like.

On a large system the electrical load is fairly constant and, except for the question of branches, can be considered as nearly uniformly distributed. If the schedule is preserved, there is unlikely to be any very great massing of cars, so that less provision has to be made for wandering of the load than in street railway service or even suburban service. This simplifies the computation of the conducting system greatly. If the rails are thoroughly bonded to the structure, and preferably also to each other, the resistance of the return circuit is extremely low. A track constant of 12 should be quite enough to allow under these circumstances, and the power demanded should not often average over seventy-five kilowatts per train at the power house. The work of rapid acceleration is the most severe contingency that must be taken into account, for elevated roads are practically level. This work will usually be not far from double the average work, at times perhaps considerably more.

An elevated structure gives an admirable opportunity for the use of polyphase motors, since the three necessary working conductors can readily be provided, and such a system has been several times suggested. In long roads an alternating distribution at high voltage might be advantageous, but intrinsically, under the necessary conditions of frequent stopping and starting, heavy loads of acceleration and large power units, there is very small reason for abandoning the continuous current motor. If the conditions of distribution demand high voltage feeders, however, a polyphase motor system can be made to meet fully the conditions of service.

Aside from elevated service the most promising field for heavy electric traction is in those special cases where the abolition of the steam locomotive is in itself desirable quite apart from the question of saving. Such cases are plentiful enough, particularly in tunnels and large terminal work in cities. The time is near when cities will defend themselves by legislative enactment against the well nigh intolerable nuisance of scores of smoking locomotives, polluting the air and distributing cinders with lavish profusion. While there was no practical means of avoiding the trouble it was endured, but with the means at hand the people are likely at any time to "get up and biff you," as the phenomenon was happily described by a certain distinguished politician lately released from the penitentiary.

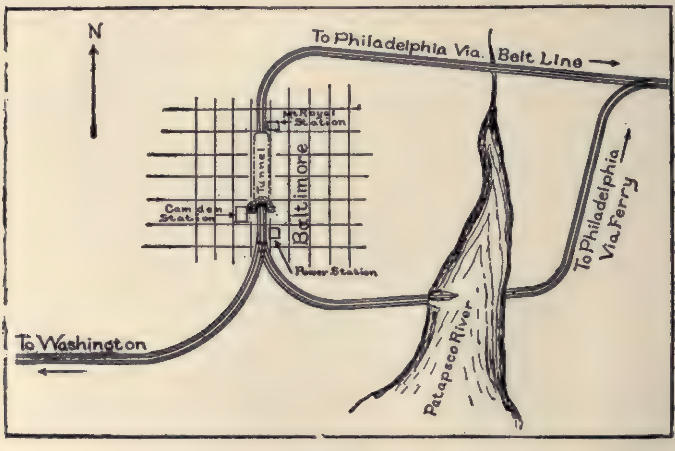


FIG. 142.

Terminal yards in the heart of a city are as at present operated simply an abominable nuisance. Tunnels in addition are often more or less dangerous. Any one who has been through the St. Louis tunnel or the St. Clair tunnel at Port Huron realizes that stalling a train would be a very serious matter, with an unpleasantly good chance for asphyxiation. Ventilation is at best difficult and seldom well done.

The now notable experiment of the Baltimore & Ohio Railroad in escaping from the tunnel difficulty has proved so successful as to leave no doubts as to the applicability of electric traction to this and all similar work.

FIG. 143.

This tunnel runs through the heart of the city of Baltimore. It is 7350 ft. long, 27 ft. maximum width and 22 ft. maximum height. Its relation to the transit through Baltimore is well shown in Fig. 142. The old route via the ferry caused continual delays and annoyance and was a constant stumbling block in the way of a fast through service to Washington. The completion of the tunnel has saved nearly twenty minutes in the time between New

York and Washington, besides facilitating the general service greatly. Unfortunately it was necessary to have a grade of nearly forty-three feet to the mile in the main tunnel, and this demanded so great power in hauling the heavy freight service as to make the smoke question exceedingly grave. In attempting to carry it on by steam locomotives just after the completion of the tunnel several men were asphyxiated, and freight service via the tunnel was dropped until the electric equipment was ready. The relatively light passenger service caused comparatively little trouble from smoke.

The first electric locomotive went into regular service on Aug. 4, 1895, and has operated with entire success since that date. The total length of the electric run, including the approaches to the tunnel, is about two miles.

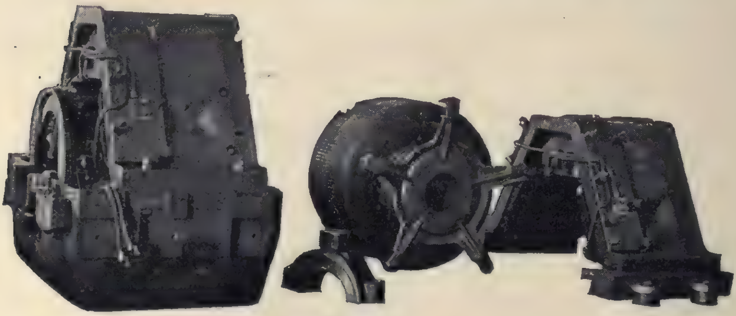


FIG. 144.

The locomotive complete is shown in Fig. 143. It is of standard gauge, 35 ft. long and 9 ft. 6¼ ins. extreme width, and weighs complete 96 tons. It is composed of two flexibly connected trucks, each having four driving wheels 62 ins. in diameter on a 6 ft. 10 in. wheel base. All the weight is, of course, on the drivers.

On each of the four driving axles is mounted a six-pole, direct connected motor of 360 nominal horse power. These motors, shown unassembled in Fig. 144, are not placed directly upon the axle. The armature shaft is a sleeve thirteen inches in exterior diameter, concentric with the axle, but with a clearance of about 1¼ ins. On this armature shaft is carried a five-armed driving spider which bears on lugs on the driving wheels through intermediary rubber cushions. The axle is thus relieved of the direct weight of the armature and there is sufficient flexibility to take up vibration due to irregularities of track. The locomotive is fitted with air brakes and air whistle, and a headlight at each end.

The supply of the immense current demanded by such a locomotive at full load was a difficult matter and the need was met by a most ingenious and effective, though from our present point of view too complicated and costly, arrangement. This was a species of reversion to the slotted tube used on some of the earliest foreign electric roads, from which current was taken by an interior brush something like a gun cleaner. In this case, however, the tube was built up of two angle irons bolted to a covering strip and weighing about ninety pounds per yard. The channels thus formed are carried on trusses in the open and suspended from the arch within the tunnel. Fig. 146 shows the character of the hollow working conductor and the

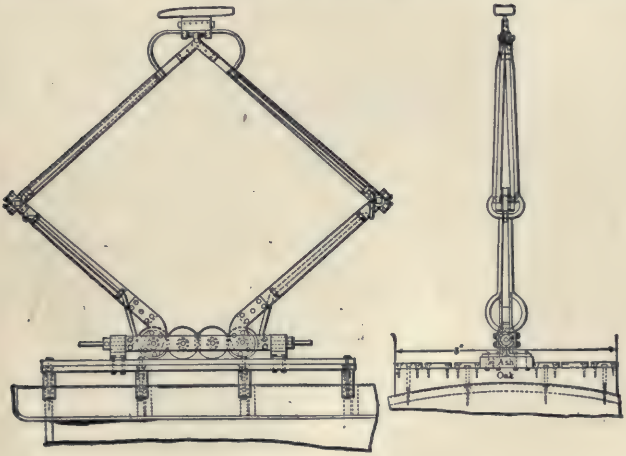


FIG. 145.

method of supporting it in the tunnel. Current is taken off by a snug-fitting brass shuttle carried on a toggle joint trolley frame, and leading to the motors by a flexible cable. Fig. 136 gives a clear idea of this trolley structure, which in practice does its work exceedingly well. Save for occasional trouble before the conductors were cleared of rust and dirt, at the very first, the arrangement has left little to be desired. The conductor in the tunnel is supported every fifteen feet, and outside the tunnel the spans are thirty to sixty feet. The trolley support has great lateral flexibility and the working conductor is normally alongside the locomotive rather than over it.

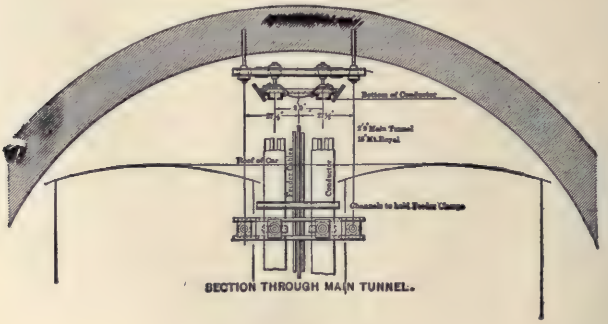


FIG. 146.

The power house is near the southern terminus of the electric system and current is taken from it to various points on the line over 1,000,000 c. m. feeder cables. The working conductor is carefully bonded at each joint by two No. 0000 bond wires.

Now as to operation. After continuous service for more than four years, the system has shown itself to be thoroughly efficient and reliable. Repairs have been light, the working conductors have been easily kept clean by running through a scraping shoe every two or three weeks, the leakage current in spite of the moisture of parts of the tunnel and very dirty insulators has been only about four amperes.

In a sample month of operation, locomotive No. 1 ran 5168 miles in regular service, hauled through the tunnel 375,000 tons in trains averaging a little over 1000 tons apiece, and did this at a total cost for labor, fuel, maintenance and incidentals, of $2186.

This means a cost of 0.58 cent per ton actually hauled, or 42.3 cents per engine mile. But with the three locomotives now in service, the labor expense at the power house is unincreased, while the other expenses increase with the number of locomotives in service. The result is greatly to reduce the cost per engine mile, probably to between twenty-five and thirty cents. The cost per engine mile for the freight service of one of the large steam railroad systems is stated to be on the average 26.1 cents., varying on the different sections between twenty-three and thirty-four cents, so that the electric traction does not differ notably in cost from steam haulage, in spite of the fact that the station is necessarily somewhat uneconomical from the frequent periods of light load. The coal consumption during the

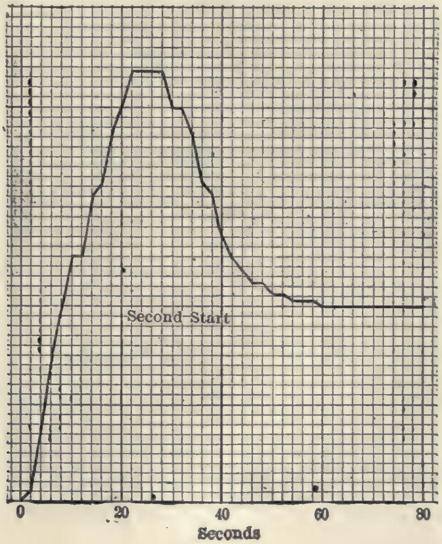


FIG. 147.

month in question was 294 tons, which shows the unfavorable load conditions very forcibly. Increased service would improve this notably. The average amperes per train during the same period were 986, showing an average input, at the usual voltage of 625, of about 600 k. w. With a 500 ton train a speed of thirty-five to forty miles per hour could be reached, and on one occasion a 1900 ton train was taken through the tunnel up grade. The drawbar pull in this case reached 63,000 lbs. Fig. 147 shows the current required for acceleration and running of a moderate train (875 tons) on the grade. The severe character of the work is sufficiently evident, and the effect on the economy of the power station of an intermittent load of this kind is obvious. The plant efficiency with the three locomotives is very materially increased.

These General Electric Baltimore & Ohio locomotives were intended for very heavy service at moderate speeds —about thirty miles per hour—but on a spurt of the engine alone up the grade more than double this has been reached.

A radically different type of locomotive intended for a different class of service is the Westinghouse-Baldwin machine shown in Fig. 148. It is built along the lines of a motor car, and is in fact a combined baggage car and locomotive. It is thirty-eight feet long and eight feet wide and weighs complete eighty tons. The eight forty-two-inch driving wheels are mounted on two trucks with unusually long wheel base. On each axle is a 250 h. p. geared motor. By this means lighter and cheaper motors can be used than with the direct coupled construction. The gearing is arranged for a full speed of seventy-five miles per hour, as the locomotive is designed for fast passenger service. As in the Baltimore & Ohio locomotives the motors are arranged for series-parallel control.

The problem of distributing power to units of so great capacity as these is serious. For tunnel work and perhaps for general work on special tracks, the centre rail distribution used on the Nantasket road or a corresponding side

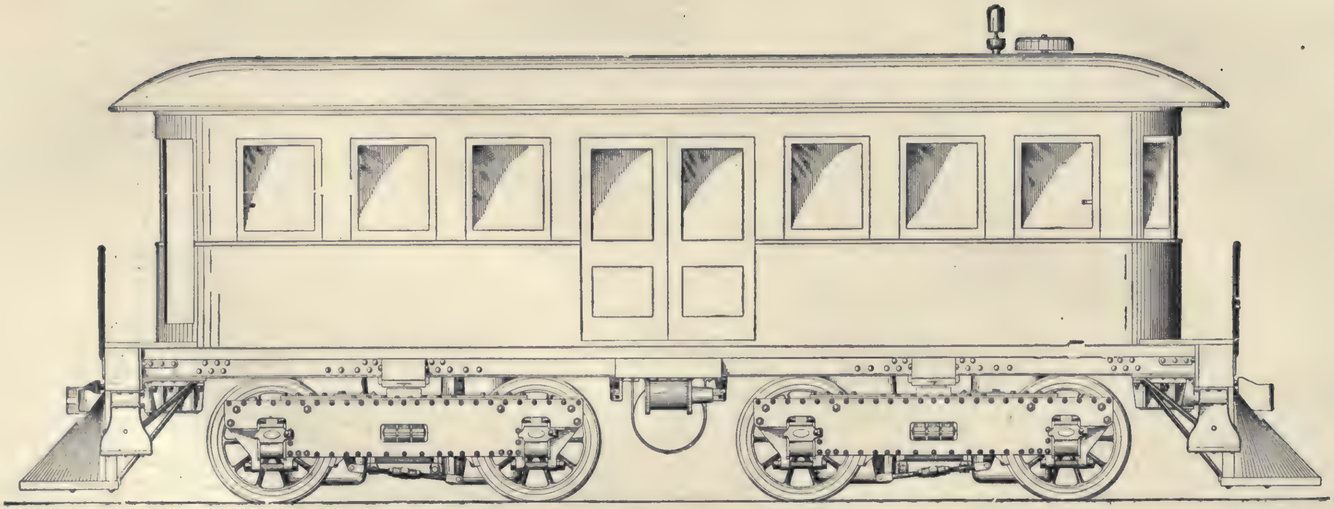


FIG. 148.

rail is to be preferred to anything as yet proposed for heavy currents. With very high voltage the overhead or side running trolley becomes necessary and with a trolley wire of large section and a pair of trolleys there is little difficulty in operating locomotives of moderate capacity even at 600 or 700 volts. The enormous capacity of the B. & O. locomotives leads to quite exceptional difficulty in taking current. At ordinary voltages the feeder section required at even moderate distances is formidable. To operate two locomotives of the B. & O. pattern on a two mile section with the power house at one terminus requires a capacity for delivering the equivalent of about 3000 amperes at the end of the line. From Plate II, using 16 as track constant, since the conductivity of the track cannot safely be taken as more than twice that of the outgoing system, the feeder area required for a transmission of 10,000 ft. at 100 volts loss is 4,800,000 c. m. Using 100 lb. center rails on a double track one gets about 2,200,000 c. m. equivalent conductivity, leaving 2,600,000 to be supplied by supplementary feeders. By allowing a little extra drop this could safely be reduced to, say, two 1,000,000 c. m. cables.

It at once becomes evident that direct supply at ordinary voltages is out of the question, except for relatively very short distances. For more extensive work we are brought back either to high voltage supply with transformers and perhaps rotary converters on the locomotive or with a low voltage working conductor supplied from transformers or rotaries along the track. Direct current throughout is barred out by the conditions of practical working except in cases similar to that just described.

For heavy special service in yards and tunnels the center rail is undoubtedly the simplest and most practical method of distribution yet tried, and for such service continuous current motors at 600 to 1000 volts with series-parallel control, leave little to be desired. If in the course of development alternating long distance service has to be linked to heavy terminal traffic, a terminal power system at moderate voltage and relatively low frequency meets the requirements. The growth of heavy electric traction in the past few years has been in the direction of rather long interurban roads worked at moderate speeds, and now and then involving freight haulage by good sized electric locomotives. Of such practice there are many admirable instances without any material change in apparatus or methods of distribution. The period has been rich in minor improvements and much experience has been acquired within a somewhat limited range. The most notable item of growth has been the complete demonstration of the success of the slotted conduit system, which however, is beyond the scope of this work except in so far as it has been noted already.

A little latter a new period of activity in methods, such as generally follows a season of standardization, may reasonably be expected.

That fast electric trains over long distances are soon coming, no one who is conversant with the art of electric traction can seriously doubt. How extensive such service will be, how far it will supersede present methods, and what methods out of those which are now practicable will survive competitive trial—these are questions for the prophet rather than the engineer.

LIST OF WORKS

—ON—

ELECTRICAL SCIENCE,

PUBLISHED AND FOR SALE BY

The Street Railway Publishing Co.,

120 Liberty Street, New York.

Hanchett's Electric Railway Motors.
The various commercial types of electric railway motors are described in full detail, including mounting and control.................................. $2.00

American Street Railway Investments.
Financial data of over 900 American city, suburban and interurban electric railways, statistics of operation, details of plant and of equipment and names of officers. Published annually.................................. 5.00

Bell's Power Distribution for Electric Railways.
Deals with the laying out and calculation of electric railway circuits. Sub-station distribution is also considered. Third Edition. Revised and enlarged.................................. 2.50

Electric Railway Motors.
By Nelson W. Perry. 238 pages, 60 illustrations.................................. 1.00

Pratt & Alden's Street Railway Roadbed.
A treatise on the construction of the roadbed, giving data as to rails, methods of track fastening and making joints, guard rails, curves, etc. 135 pages, 157 illustrations.................................. 2.00

Reference Book of Tables and Formula for Electric Street Railway Engineers.
By E. A. Merrill. Second Edition. Flexible Morocco. 128 pages. Interleaved with blank pages.................................. 1.00

Shop and Road Testing of Dynamos and Motors.
By E. C. Parham and J. C. Shedd. 520 pages, 163 illustrations........... 2.00

Bell's Electric Power Transmission: a Practical Treatise for Practical Men.
The best treatise yet written on the practical and commercial side of electrical power transmission. Third Edition. Revised and enlarged.... 3.00

Electro-Dynamic Machinery.
By E. J. Houston, Ph. D., and A. E. Kennelly, D. Sc. A text-book on continuous-current dynamo-electric machinery for electric-engineering students of all grades. 361 pages, 232 illustrations.................................. 2.50

Practical Calculation of Dynamo Electric Machines.
A manual for electrical and mechanical engineers, and a text-book for students of electro-technics. By A. E. Wiener. 683 pages, 375 illustrations 2.50

The Theory and Calculation of Alternating Current Phenomena.
By Charles Proteus Steinmetz. Third Revised and greatly enlarged Edition.................................. 4.00

ELECTRO-TECHNICAL SERIES.

BY E. J. HOUSTON AND A. E. KENNELLY.

Alternating Electric Currents. 225 pages, 77 illustrations	$1.00
Electric Arc Lighting. 383 pages, 155 illustrations	1.00
Electric Heating. 290 pages, 86 illustrations	1.00
Electric Incandescent Lighting. 449 pages, 146 illustrations	1.00
Electric Street Railways. 367 pages, 158 illustrations	1.00
Electric Telegraphy. 448 pages, 163 illustrations	1.00
Electro-Therapeutics. Second Edition. 452 pages, 147 illustrations	1.00
Magnetism. 294 pages, 94 illustrations	1.00
The Electric Motor. 377 pages, 122 illustrations	1.00
The Electric Telephone. 412 pages, 143 illustrations	1.00
Electrical Engineering Leaflets, Containing the Underlying Principles of Electricity and Magnetism. By Prof. E. J. Houston and A. E. Kennelly.	
ELEMENTARY GRADE—suited to the study of Electrical Artisans, Wiremen and to Elementary Students. 299 pages, 149 illustrations. 8 vo. cloth	1.50
INTERMEDIATE GRADE—suited to Students in High Schools, or Colleges, and those beginning the study of Electrical Engineering. 300 pages, 140 illustrations. 8 vo, cloth	1.50
ADVANCED GRADE—suited to Students taking Technical Courses in Electrical Engineering. 280 pages, 121 illustrations. 8 vo. cloth. New York, 1895	1.50
Electricity and Magnetism. Being a series of advanced primers. By Edwin J. Houston, Ph. D. Second Edition. 318 pages, 117 illustrations	
Electrical Measurements and Other Advanced Primers of Electricity. By Edwin J. Houston, Ph. D. 429 pages, 169 illustrations	1.00
The Electrical Transmission of Intelligence and Other Advanced Primers of Electricity. By Edwin. J. Houston, Ph. D. 330 pages, 88 illustrations	1.00
Electricity One Hundred Years Ago and To-day. By Edwin J. Houston, Ph. D. 199 pages, illustrated	1.00
Gerard's Electricity. With chapters by Dr. Louis Duncan, C. P. Steinmetz, A. E. Kennelly and Dr. Cary T. Hutchinson. Translated under the direction of Dr. Louis Duncan. 392 pages, 112 illustrations	2.50
Miller's American Telephone Practice. A comprehensive treatise, including descriptions of apparatus, line construction, exchange operation, etc. Third Edition. Revised and enlarged.	3.00
Dobbs, A. E. Practical features of Telephone Work. Illustrated. 12mo, cloth. New York, 1898	.75
Emmet, William L. R. Alternating Current Wiring and Distribution. Contains a very clear account of the principles of alternating currents from the practical point of view. and of their distribution and application to lighting and power. Polyphase currents, the load factor, the effects of capacity and inductance, and the various losses in distribution, are simply explained, no mathematics beyond arithmetic being used. 76 pages, 29 illustrations. 16mo, cloth. New York, 1898	1.00
Universal Wiring Computer. For Determining the Sizes of Wires for Incandescent Electric Lamp Leads, and for Distribution in General without Calculation, with Some Notes on Wiring and a Set of Auxiliary Tables. By Carl Hering. Third Thousand. 44 pages, 4 charts	1.00
Dictionary of Electrical Words, Terms and Phrases. By Edwin J. Houston, Ph. D. Fourth edition. Greatly enlarged.	
900 double column octavo pages, 582 illustrations	7.00
Pocket edition, 945 pages, cloth	2.50
Pocket edition, 945 pages, leather	3.00